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SECTION 11

ALTERNATE SOURCES OF POWER

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11.1 TRADITIONAL ENERGY SOURCES

BY RAMESH BANSAL

Electricity has been generated for the purpose of powering human needs for more than 120 years from various energy sources. The importance of dependable electricity generation was revealed when it became apparent that electricity was useful for providing heat, light, and power for human activities. Today, traditional (conventional) sources of power generation are fossil fuels (coal, petroleum, natural gas), hydro and nuclear power systems.

11.1.1 Coal

The primary sources for coal are China, the United States, and the former USSR. These countries have 75% of the coal reserves. Coal was the first fossil fuel used for producing electricity. Electricity is produced at a coal-fired fossil plant by the process of heating water in a boiler to about 540°C to produce steam. The steam, under tremendous pressure of about 130 Kg/cm², flows into a turbine, which spins a generator to produce electricity. Many environmental problems are associated with the use of coal including nitrous oxides, sulfur oxides, CO₂, as well as particulate matter is released when coal is burned. Nitrous oxides and sulfur oxides cause acid rain and CO₂ is responsible for global warming.

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11.1.2 Crude Oil (Petroleum)

The use of oil started after the 1860s. Oil is liquid hydrocarbon. There are three main products of oil: kerosene, fuel oil, and gasoline. About 75% of the oil production is controlled by OPEC (Organization of Petroleum Exporting Countries), which was formed in 1973. OPEC can negotiate as a block to sell their oil, and thus are able to set higher prices. The advantages of oil are easy to handle, store, and transport. Also, it is used for things other than energy: productions of plastic, lubrication, etc. While oil burns cleaner than coal, the same pollutants are produced and the same environmental problems are associated with oil production, transport, and combustion.

11.1.3 Natural Gas

Natural gas is available in three types: methane, propane, and butane. Natural gas is often found in association with crude oil. The largest reserves are found in the Persian Gulf countries. Advantages of natural gas are that it burns cleaner than the other fossil fuels, less nitrous oxides and sulfur oxides are produced, and less particulate matter, but CO₂ is still produced. Combustion turbines can run on natural gas or low-sulfur fuel oil and are designed to start quickly to meet the demand for electricity during peak operating periods. Air enters at the front of the unit and is compressed, mixed with natural gas or oil, and ignited. The hot gas then expands through turbine blades to turn the generator and produce electricity.

11.1.4 Hydro

Hydroelectric power is a form of power that utilizes the energy released by water falling on the turbine blades that rotates the generator to produce electricity. Hydroelectricity is a renewable energy source, since the water that flows in rivers has come from precipitation such as rain or snow. The energy that may be extracted from water depends not only on the volume but also on head (the difference in height between the water crest [or source] and the water outflow).

TABLE 11-1 Installed Hydroelectric Capacity

Country	Hydroelectric installed capacity (MW)
United States	79,511
Canada	66,954
China	65,000
Brazil	57,517
Russia	44,000
Norway	27,528

Hydroelectric power supplies about 20% of the world's electricity. Norway produces virtually all of its electricity from hydro, while Iceland and Austria produce 83% and 67%, respectively, of their electricity from hydro. Countries with their hydroelectric installed capacities are shown in Table 11-1.

The world's largest hydroelectric power stations in operation are at Itaipu, Brazil with an installed capacity of 12,600 MW and Three Gorges Dam, China with installed capacity of 18,200 MW, which is scheduled to be completed by 2009.

The chief advantage of hydro systems is elimination of the cost of fuel. Hydroelectric plants are immune to price increases for fossil fuels and do not require imported fuel. Hydroelectric plants tend to have longer lives than fossil-fuel-fired generation, with life spans of 50 to 100 years. Operation and maintenance costs also tend to be low since plants are generally heavily automated and have fewer personnel on-site during normal operation. Hydroelectric plants are pollution free. Since the generating units can be started and stopped quickly, they can follow system loads efficiently, and may be able to reshape water flows to more closely match daily and seasonal system energy demands. Concerns have been raised by environmentalists that large hydroelectric projects might be disruptive to surrounding aquatic ecosystems. Another disadvantage of hydroelectric dams is the need to relocate the people living where the reservoirs are planned.

11.1.5 Nuclear Fuel

The first commercial nuclear power stations started operation in the 1950s. There are now some 440 commercial nuclear power reactors operating in 31 countries, with over 364,000 MW of total capacity. Main countries producing electricity from nuclear power are the United States, France, and

Japan, having installed capacities of 97,585, 63,474, and 46,343 MW, respectively, as of May 2005. Nuclear fission, or the splitting of atoms of ^{235}U , releases energy, which is used to heat water and produce steam, which drives turbines to produce electricity.

Although uranium is mined, very little of it is needed compared to coal or oil, so the mining itself is not as big an environmental concern as it is for the fossil fuels. Advantages of nuclear power include the lack of pollution-causing emissions. There are great dangers associated with nuclear power production, however, since a by-product of the process, plutonium, can be used to make nuclear weapons. In addition, there are problems associated with how to dispose off nuclear waste and how to deal with decommissioning old power plants that are no longer productive.

The two most common types of nuclear power plants are boiling water reactor (BWR) and pressurized water reactor (PWR), both using water as coolant. In BWR plants, the water is allowed to boil in the reactor core, the steam is then passed through the turbine, which runs the generator to produce electricity. In PWR plants, there are two more cycles linked by the heat exchanger. In PWR, fuel rods are placed in the reactor vessel to make up the core—the part of the plant that produces heat. When a uranium atom splits in the process called nuclear fission, it gives off energy in the form of heat. To regulate the heat-producing process, control rods and borated water are used. The borated water speeds up or slows down the fission process, and the control rods shut down the reaction when they are inserted between the fuel rods. A nuclear plant works in much the same way that a dam or fossil fuel plant does, in which large turbine blades are used to run a generator to produce electricity. At a hydroelectric dam, the force of the falling water spins the turbine blades, while at a coal-fired or nuclear plant, the force of steam spins the blades. A nuclear plant, however, uses uranium instead of coal as a fuel to make steam.

11.2 RENEWABLE ENERGY TECHNOLOGIES

BY RAMESH BANSAL

The energy crisis, which began in 1973, caused petroleum supplies to decrease and prices to rise exorbitantly. This crisis forced developing countries to reduce or postpone important development programs, so they could purchase petroleum to keep their economies operating. It created the urgent necessity to find and develop alternative energy sources, as other fossil fuels (coal, oil, and natural gas), nuclear energy, and renewable energy resources.

There are concerns about nuclear energy because of the associated accident risks; waste disposal difficulties, nuclear terrorism, and nuclear weapon proliferation are dangerous in themselves. Acquiring nuclear energy from the industrialized world could, moreover, result in greater technological and economic dependence on developed countries. World's proved fossil fuel resources might be exhausted in about 100 years, thus making situation alarming. A more feasible alternative to petroleum, coal, and nuclear reactors in developing countries is the *direct* and *indirect* use of solar energy, which is renewable, abundant, decentralized, and nonpolluting.

Each day, the sun sends to earth many thousands of times more energy than we attain from other sources (the equivalent of 200 times the energy consumed by the United States in 1 year). This energy can be captured *directly* as radiation or—even more significantly—*indirectly* in waterfalls, wind, and green plants. Taking into account that the technology needed for exploiting renewable energy resources is simple and relatively economical, it is important from a strategic point of view that energy planning in Third World countries, particularly in the humid tropics, be oriented to developing the solar alternative. It offers them one of the few opportunities to develop independently of the industrialized countries. This section briefly describes various renewable energy sources, that is, solar, wind, small hydro, biomass, geothermal, tidal, magnetohydrodynamic (MHD), and ocean thermal energy conversion (OTEC).

11.2.1 Solar Energy

Solar power describes a number of methods of harnessing energy from the light of the sun. It is already in widespread use where other supplies of power are absent such as in remote locations and in space. As the earth orbits the sun, it receives approximately $1,020 \text{ W/m}^2$ at sea level.

Solar power may be classified as direct and indirect. Direct solar power involves only one transformation into a usable form, for example, sunlight hits a photovoltaic cell to create electricity and warms the surface or heats the water when the light is converted to heat by interacting with matter. Indirect solar power involves more than one transformation to reach a usable form. Many other types of power generation are indirectly solar-powered, for example, (i) vegetation use photosynthesis to convert solar energy to chemical energy, which can later be burned as fuel to generate electricity; (ii) energy obtained from oil, coal, and peat originated as solar energy captured by vegetation in the remote geological past and fossilised; (iii) hydroelectric dams and wind turbines are indirectly powered by solar energy through its interaction with the earth's atmosphere and the resulting weather phenomena; (iv) energy obtained from methane (natural gas) may be derived from solar energy either as a biofuel or fossil fuel; (v) ocean thermal energy production uses the thermal and gradients that are present across ocean depths to generate power.

Solar power can also be classified as passive or active. *Passive solar systems* are systems that do not involve the input of any other forms of energy apart from the incoming sunlight. *Active solar systems* are those that use additional mechanisms such as circulation pumps, air blowers, or automatic systems that aim collectors at the sun. Effective use of solar radiation often requires the radiation (light) to be focused to give a higher intensity beam, that is, parabolic dish, parabolic trough, etc., are used to concentrate light at a point or a line. At the focus, high-concentration photovoltaic cells (solar cells) or a thermal energy "receiver" may be placed. Most of the solar energy used today is harnessed as heat or electricity. Solar design aims the use of architectural features to replace the use of grid electricity and fossil fuels with the use of solar energy and decrease the energy needed in a home or building with insulation and efficient lighting and appliances. Following are the main applications of solar energy:

Photovoltaic systems: Solar cells, also known as photovoltaic cells, use the photovoltaic effect of semiconductors to generate electricity directly from the sunlight. Because of high manufacturing costs, their use has been limited until recently. One cost-effective use has been in very low-power devices such as calculators with LCDs. Another use has been in remote applications such as roadside emergency telephones, remote sensing, cathodic protection of pipelines, and limited to isolated home power applications. A third use has been to power orbiting satellites and other spacecraft. However, the continual decline of manufacturing costs (dropping at 3% to 5% a year in recent years) is expanding the range of cost-effective uses.

Solar heating: Solar hot water systems are quite common in some countries where a small flat panel collector is mounted on the roof and is able to meet most of a household's hot water needs. Cheaper flat panel collectors are also often used to heat swimming pools, thereby extending the swimming season. There are some new applications of thermal hot water, like air cooling, currently under development.

Solar cooker: Taps the sun's power in an insulated box, which has been successfully used for cooking. Solar cooking is helping many developing countries both by reducing the demands for local firewood and maintaining a cleaner environment for the cooks.

11.2.2 Wind Energy

Among the renewable sources of energy available today for generation of electrical power, wind energy stands foremost because of the no pollution, relatively low capital cost involved and the short gestation period required. Wind-powered systems have been widely used since the tenth century for water pumping, grinding grain, and other low-power applications. There were several early attempts to build large-scale wind-powered systems to generate electricity. Recently, wind turbine of 4.5 MW and rotor diameter of more than 112.8 m has been in operation.

Today, wind energy is the fastest growing energy source. Presently, wind power meets the electricity needs of more than 35 million people. Globally, the wind power industry employs around 70,000 people and is worth more than \$5 billion. According to Global Wind Energy Council (GWEC), global wind power capacity has increased from 7,600 MW at the end of 1997 to 47,337 MW by February 2005. Main countries producing electricity from wind are Germany, Spain, the United States, Denmark, and India, having their installed capacities 16,629, 8,263, 6,470, 3,117,

and 3,000 MW, respectively, by February 2005. Today, wind power accounts for about 0.4% of the world's electricity demand. An analysis by the European Wind Energy Association (EWEA) shows that there are no technical, economic, or resource limitations that prevent wind power from developing to nearly 12% of the world's electricity supply by 2020, but with strong political commitment worldwide, the wind energy industry could install an estimated 1200,000 MW by 2020.

The total wind power P_w that is available to a wind turbine is given by

$$P_w = (\rho AV^3)/2 \quad (11-1)$$

where ρ is the density of the air in kg/m^3 , A is the exposed area in m^2 , and V is the velocity in m/s . The maximum power that can be realized from a wind system is 59.3% of the total wind power. The power in the wind is converted to mechanical power with an efficiency (coefficient of performance) c_p , which is transmitted to the generator through a mechanical transmission with efficiency n_m , and is converted to electricity with an efficiency n_g . The electrical power output is then

$$P_e = c_p n_m n_g P_w \quad (11-2)$$

For a given system, P_w and P_e will vary with wind speed. As the wind increases from a low value, the turbine is able to overcome all mechanical and electrical losses and start delivering electrical power to the load at cut-in speed V_C . The rated power output of the generator is reached at rated wind speed V_R . Above V_R , some wind power is spilled to maintain constant power output. At the furling speed V_F , the machine is shut down to protect it from high winds. Seasonal and diurnal variation has significant effect on wind. Other factor, which affects power from wind, is height of wind turbine. Wind speed increases with the height because of friction at the earth's surface.

There are a number of ways of classifying wind systems, for example, according to size of power output, rotational speed of wind turbines, orientation of wind turbines, etc. According to the size of power output, wind systems may be classified, for example, as small, medium, and large.

According to the rotational speed, wind turbines are classified as fixed speed and adjustable speed generators. In fixed speed generators, the rotor is held constant by continuously adjusting the blade pitch and/or generator characteristics. For synchronous generators, the requirement of constant speed is very rigid and only minor fluctuations of about 1% for short durations could be allowed. As the wind fluctuates, a control mechanism becomes necessary to vary the pitch of the rotor so that the power derived from the wind system is held fairly constant. Induction generators with small negative slip can also be considered as constant speed. Induction generators are simpler than synchronous generators. They are easier to operate, control and maintain, have no synchronization problem, and are economical. Modern high-power wind turbines are capable of adjustable speed operation. Key advantages of adjustable speed generators compared to fixed speed generators are that they are cost effective, provide simple pitch control, and yield higher output for both low and high wind speeds.

According to the orientation of turbines, wind turbines are classified as horizontal and vertical axis machines. In horizontal axis wind turbines (HAWT), the axis of rotation is parallel to the direction of the wind. Depending upon the number of blades these may be classified as single-bladed, double-bladed, three-bladed, multibladed, and bicycle-bladed. In vertical axis wind turbines (VAWT), the axis of rotation is perpendicular to the direction of wind. These machines are also called *crosswind axis machines*. Main designs of vertical axis machines are Savonius and Darrieus rotors. The principal advantages of VAWT over conventional HAWT are that VAWT are omnidirectional, that is, they accept the wind from any direction. The vertical axis rotation also permits mounting the generator and gear at the ground level. On the negative side VAWT requires guy wires attached to the top for the support, which may limit its application particularly for the offshore sites.

Wind speeds over the open ocean average 30% to 50% higher than on land, while turbulence is reduced because of the absence of surface obstructions such as hills, trees, and buildings. Since power increases as the cube of the wind speed, the substantial increases in output that can be achieved in offshore wind power systems can more than offset the increased cost of sitting wind turbine in water. Offshore designs are therefore made to meet different requirements. Wind machines must have marine grade components, seals, and coatings to protect them from corrosion. In Europe, offshore projects are now springing up off the coasts of Denmark, Sweden, the United Kingdom, France, Germany, Belgium, Ireland, the Netherlands, and Scotland.

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11.2.3 Small Hydropower

Although this technology is not new, its wide application to small waterfalls and other potential sites is new. It is best suited to high falls with low volume, such as occur in high valleys in the mountains. It is the application of hydroelectric power on a commercial scale serving a small community. These plants are classified by power and size of waterfall. A generating capacity of up to 10 MW is becoming generally accepted as the upper limit of small hydro, although this may be stretched up to 30 MW in some countries. Small hydro can be further subdivided into mini-hydro, usually defined as less than 1,000 kW, and micro-hydro which is less than 100 kW.

Hydroelectric power is the technology of generating electric power from the movement of water through rivers, streams, and tides. Water is fed via a channel to a turbine where it strikes the turbine blades and causes the shaft to rotate. To generate electricity, the rotating shaft is connected to a generator which converts the motion of the shaft into electrical energy. Small hydro is often developed using existing dams or through development of new dams whose primary purpose is river and lake water-level control, or irrigation. A small-scale hydroelectric facility requires a sizeable flow of water and a reasonable height of fall of water, called the *head*. Another advantage of using water resources is that hydraulic works can be made simple, and large constructions, such as dams, are not usually required. When dams are necessary, they affect less area than in lower zones because of the steepness of the terrain. Dams, which exploit the kinetic energy of water by raising small quantities of water to heights through the use of regulated pressure valves, can provide water for domestic uses and for agriculture in areas that are moderately higher than adjacent water courses. Another interesting possibility is the utilization of induction generators for supplementing small hydroelectric plants, which require lower initial costs and have technical operation advantages over synchronous generators.

11.2.4 Biomass Energy

Biomass contributes 14% of the world's primary energy demands, and in developing countries it constitutes 35% of the primary energy supply. Biomass is an energy carrier that can be used in solid, liquid, and gaseous forms, and is a versatile source of energy that can produce electricity, heat, transport fuel, and can be stored conveniently. Energy production of biomass units ranges from small scale to multi-megawatt size. The main biomass conversion technologies are biomass gasifiers and biogas generation.

Biomass is organic nonfossil material. In other words, biomass is all plant, trees, and animal matter on the earth's surface. Humans, domestic animals, and crops comprise somewhere between 40% to 60% of the earth's biomass. In many ways biomass can be considered as a form of stored solar energy. The energy of the sun is "captured" through the process of photosynthesis in growing plants. Biomass is sometimes burned as fuel for cooking and to produce electricity and heat. Methanol and ethanol are popular sources of alternative energy produced by the fermentation of organic matter, such as manure, under anaerobic conditions. The use of biogas is encouraged because methane burns with a clean flame and produces little pollution. Digestion of manure occurs in a digester, which must be strong enough to withstand the buildup of pressure and must provide anaerobic conditions for the bacteria inside.

11.2.5 Geothermal Energy

Electricity from geothermal energy is generated by utilizing naturally occurring geological heat sources. Geothermal-generated electricity was first produced at Larderello, Italy, in 1904. Since then, the use of geothermal energy for electricity has grown worldwide to about 8,000 MW of which the United States produces 2,700 MW. The largest dry steam field in the world is The Geysers, about 90 miles north of San Francisco, began in 1960, which produces 2,000 MW. Geothermal power is generated in over 20 countries around the world including Iceland (producing 17% of its electricity from geothermal sources), the United States, Italy, France, New Zealand, Mexico, Philippines, Indonesia, and Japan.

Large scale electrical generation is possible in areas near geysers or hot springs by utilizing naturally occurring steam, superheated ground water, or using geothermal heat to heat a heat-transfer fluid. Experiments are in progress to make deep wells into hot dry rocks (HDR), which can be

economically used to heat water pumped down from the surface. Geothermal areas without steam are called HDR. HDR programs are currently being developed in Australia, France, Switzerland, and Germany. Magma (molten rock) resources offer extremely high-temperature geothermal opportunities, but existing technology does not allow recovery of heat from these resources.

Although geothermal sites are capable of providing heat for many decades, eventually they are depleted as the ground cools. It can be said that the geothermal resource is not strictly renewable in the same sense as the hydro resource. Currently, there are few geothermal resource areas capable of generating electricity at a cost competitive with other energy sources, such as natural gas and coal. Some do not have a high enough temperature to produce steam and others don't have the water to produce steam, which is necessary for current plant designs. Also, instead of producing electricity, lower temperature areas can provide space and process heating.

11.2.6 Tidal Energy

Tidal power is a means of electricity generation achieved by capturing the energy contained in moving water mass due to tides. Two types of tidal energy can be extracted: kinetic energy of currents due to the tides and potential energy from the difference in height (or *head*) between high and low tides. The extraction of potential energy involves building a barrage. The barrage traps a water level inside a basin. Head is created when the water level outside of the basin changes relative to the water level inside. The head is used to drive turbines. In any design this leads to a decrease of tidal range inside the basin, implying a reduced transfer of water between the basin and the sea. This reduced transfer of water accounts for the energy produced by the scheme.

Tidal power is classified as a renewable energy source, because tides are caused by the orbital mechanics of the solar system and are considered inexhaustible within a human time frame. The root source of the energy comes from the slow deceleration of the earth's rotation. The moon gains energy from this interaction and is slowly receding from the earth. Tidal power has great potential for future power and electricity generation because of the total amount of energy contained in this rotation. The efficiency of tidal power generation largely depends on the amplitude of the tidal swell, which can be up to 10 m where the periodic tidal waves funnel into rivers and fjords. Selection of location is critical for a tidal power generator. The potential energy contained in a volume of water is

$$E = xMg \quad (11-3)$$

where x is the height of the tide, M is the mass of water, and g is the acceleration due to gravity. Therefore, a tidal energy generator must be placed in a location with very high-amplitude tides. Suitable locations have been found in the former USSR, the United States, Canada, Australia, Korea, the United Kingdom and in many other countries.

11.2.7 Magnetohydrodynamic Generation

MHD power generation is a method of direct conversion of heat into electrical energy. Kinetic energy of the fluid is converted into electrical power by the interaction of the electrical conducting fluid under the influence of magnetic field. In thermal generation of electric energy, the heat released by the fuel is converted to rotational mechanical energy by means of a thermocycle. The mechanical energy is then used to rotate the electric generator. Thus, two stages of energy conversion are involved in which the heat to mechanical energy conversion has inherently low efficiency. Also, the rotating machine has its associated losses and maintenance problems. In MHD technology, the hot gases produced by the combustion of fuel without the need for mechanical moving parts directly generate electric energy.

The fluid conductor is typically an ionized flue gas resulting from combustion of coal or other fossil fuels. The conductive fluid flows through the magnetic field, inducing an electric field by the Faraday effect. The electric field is orthogonal to both the fluid velocity and magnetic field vectors. As a result, potential difference is developed between the two walls of the duct. The direct current generated is converted to alternating current by a solid-state inverter. A typical MHD plant requires combustion gases of about 2,650°C and a pressure of 500 to 1,000 kPa. Commercial scale MHD

plants will use superconducting magnets. To achieve superconducting properties, the magnets must be cooled to around 4K. The MHD technology is in the relatively early development stage, although test data indicate that there are no fundamental barriers for commercialization of MHD technology. Several prototype units are being tested in the United States.

11.2.8 Ocean Thermal Energy

OTEC is an energy technology that converts solar radiation to electrical power. OTEC systems use the ocean's natural thermal gradient—the fact that the ocean's layers of water have different temperatures to drive a power-producing cycle. As long as the temperature between the warm surface water and the cold deep water differs by about 20°C, an OTEC system can produce a significant amount of power. The oceans are thus a vast renewable resource, with the potential to help us produce billions of watts of electrical power. The potential is estimated to be about 10^{13} W of base load power generation. The cold, deep seawater used in the OTEC process is also rich in nutrients, and it can be used to culture both marine organisms and plant life near the shore or on land.

The main advantages of OTEC are that (i) it uses clean, renewable, and natural resources, (ii) warm surface seawater and cold water from the ocean depths replace fossil fuels to produce electricity, (iii) suitably designed OTEC plants produce negligible pollution, and (iv) it can produce freshwater as well as electricity, which is a significant advantage in island areas where freshwater is limited. The disadvantages of OTEC are (i) OTEC-produced electricity at present costs more than the electricity generated from fossil fuels at their current costs, (ii) plants must be located where a difference of about 20°C occurs year-round, (iii) ocean depths must be available fairly close to shore-based facilities for economic operation, and (iv) no energy company may put money in this project because it only had been tested in a very small scale.

OTEC covers 71% of the earth's surface and acts as a natural collector and store of solar energy. On an average day, 60 million km² of tropical seas absorb an amount of solar radiation equivalent in heat content to about 245 billion bbl of oil. The main countries in which OTEC plants exist are the United States with installed capacity of 100 MW, the United Kingdom, the Netherlands, Japan, and Taiwan with capacity of about 10 MW. By 2010, about 1,000 OTEC plants are expected to be installed in the range 1 to 100 MW to generate about 50,000 MW.

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11.3 SOLAR ENERGY

By AHMED ZOBA, CAIRO (Egypt) University

The sun's energy arrives on earth in the primary form of heat and light. Other aspects of solar radiation are less easily perceived and their detection often requires sophisticated equipment. All solar radiation travels through space in waves, and it is the length of these waves (the shortest is less than a millionth of an inch, the longest more than a thousand yards) by which all solar radiation is classified. The aggregate of all radiation aspects of the sun is called the *solar spectrum*.

There are two important facets about the solar spectrum:

1. While the sun emits radiation in all wavelengths, it is the short wavelength radiation that accounts for the majority of energy in the solar spectrum. For example, the portion of the spectrum perceived as the visible light is a relatively small segment compared to the variety of spectrum wavelengths, yet accounts for 46% of the energy radiating from the sun. Another 49%, which is perceived as heat, is derived from the infrared band of the spectrum.
2. The proportion of different wavelengths in the solar spectrum does not change and therefore the energy output of the sun remains constant. A measurement of this phenomenon is known as the *solar constant*, defined as the amount of heat energy delivered by solar radiation to a square foot of material set perpendicular to the sun's rays for 1 h at the outer edge of the earth's atmosphere. The solar constant measurement is about 429.2 Btu with minimal changes over the year. The energy measured as the solar constant is not a measure of the amount of solar energy that actually reaches the earth's surface, since as much as 35% of all the solar radiation intercepted by the earth and its surrounding atmosphere is reflected back into space. Additionally, water vapor and atmospheric gases absorb another 15%. As a global average only about 35% to 40% of the solar radiation entering the atmosphere actually reaches the earth's surface.

11.3.1 Solar Constant

The solar constant is the amount of energy received at the top of the earth's atmosphere on a surface oriented perpendicular to the sun's rays (at the mean distance of the earth from the sun). The generally accepted solar constant of 1,368 W/m² is a satellite measured yearly average.

In order to calculate the solar constant, the following equation is used:

$$S = E(\text{sun}) \times (R(\text{sun})/r)^2 \quad (11-4)$$

where S = solar constant

E = surface irradiance of the sun

R = 6.96×10^5 km = radius of the sun

r = 1.5×10^8 km = average sun-earth distance

The solar constant is not really constant; this is due to the variation of the intensity of the sun due to sunspots. *Sunspots* are convective activity in the upper layer of the sun. Their number varies in cycles of 22 years and influences solar luminosity. Another reason why S varies is because of changes in the average distance earth-sun "eccentricity." The eccentricity varies regularly with periods of about 100,000 and 400,000 years. The maximum change in S associated with variation in eccentricity is about 0.1%. The angle of tilt of the earth's axis of rotation varies between 22° and 24.5° with a periodicity of about 40,000 years.

Table 11-2 presents some values of solar constants in kWh/m²/day for different countries in the world.

11.3.2 Radiation Received at Earth's Surface

The earth gets only 2 billionths of the sun's energy, but that is still a lot. However, life (through photosynthesis) uses only 0.023% of the energy that reaches the surface of the earth (Fig. 11-1).

TABLE 11-2 Solar Constants in kWh/m²/day for Different Countries in the World

Country	State/City	Latitude	Longitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year avg
DZ	Alger	36° 50" N	3° E	2.22	2.94	3.87	5	5.88	6.69	7.23	6.48	5.15	3.53	2.43	2.02	4.45
EG	Cairo	29° 35" N	31° 09" E	3.39	4.17	5.24	6.49	7.11	8	7.88	7.4	6.42	5.07	3.86	3.19	5.68
GM	Gambia	13° 28" N	16° 39" W	5.01	5.93	6.67	6.92	6.72	6.06	5.48	5.09	5.3	5.67	5.36	4.95	5.76
LR	Liberia	6° 30" N	9° 30" W	5.43	5.72	5.59	5.31	5.11	4.61	4.25	4.19	4.67	5.13	5.24	5.2	5.03
KE	Nairobi	1° 16" S	36° 48" E	6.05	6.24	6.07	5.7	5.42	5.14	4.88	5.09	5.78	6.03	5.48	5.6	5.62
CA	San Francisco	38° 31" N	121° 30" W	2.35	3.33	4.42	5.95	6.84	7.39	7.55	6.51	5.75	3.92	2.65	2.06	4.89
CO	Denver	39° 45" N	104° 52" W	2.25	3.2	4.32	5.61	6.11	6.71	6.5	5.86	5.47	4.01	2.59	1.98	4.55
CT	Hartford	41° 44" N	72° 39" W	1.7	2.43	3.48	4.07	5.14	5.58	5.38	5.04	4.13	2.91	1.81	1.42	3.59

- Thirty-four percent of the sun's energy is reflected back into space by snow and clouds. This reflective quality of a planet is called its *albedo*.
- Forty-two percent of the energy goes to warm the land and water. The warmth of the earth is constantly being radiated into space, and the sun's energy replenishes this warmth.
- The water cycle—evaporation and precipitation—uses 23% of the solar energy.
- Winds and ocean currents use 1%.

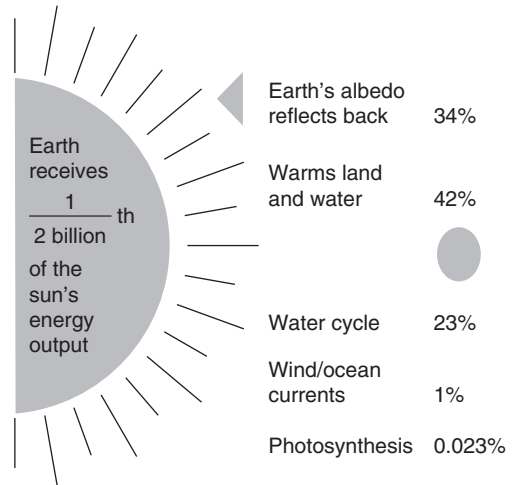


FIGURE 11-1 Percent of the sun's energy on the surface of the earth.

11.3.3 Flat-Plate Collector

A typical *flat-plate collector* (Fig. 11-2) is an insulated metal box with a glass or plastic cover, called the glazing, and a dark-colored absorber plate. Low-iron glass is a common glazing material for flat-plate as it gets high percentage of the total available solar energy. Simultaneously, only very little of the heat emitted by the absorber escapes the cover (greenhouse effect).

In addition, the transparent cover prevents wind and breezes from carrying the collected heat away (convection). Together with the frame, the cover protects the absorber from adverse weather conditions. Typical frame materials include aluminum and galvanized steel; sometimes fiberglass-reinforced plastic is used.

The insulation on the back of the absorber and on the sidewalls lessens the heat loss through conduction. Insulation is usually of polyurethane foam or mineral wool, though sometimes mineral fiber insulating materials like glass wool, rock wool, glass fiber, or fiberglass are used.

Flat-plate collectors fall into two basic categories: air and liquid. Both types can be either glazed or unglazed (according to the previously mentioned classification).

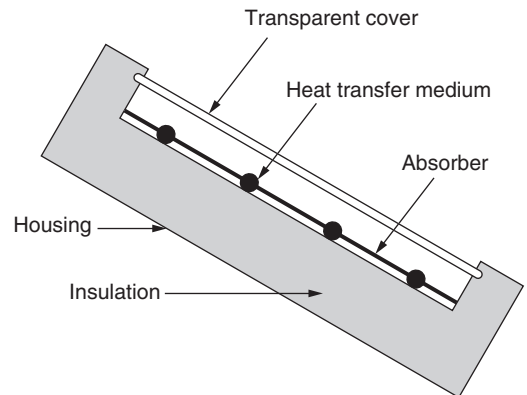


FIGURE 11-2 Elements of the basic flat-plate collector.

11.3.4 Collector Efficiency

The collector performance is evaluated in terms of collector efficiency, the ratio of the energy collected to that incident on the collector, usually expressed as a percentage. At a fixed rate of solar insulation, the collector efficiency of a given collector decreases with temperature difference between the collector and the surrounding air. Thus, there is a trade-off between temperature of collection and amount of energy collected. If high collection temperatures are desired, a larger amount of collector surface is needed than would be required to gather the same amount of energy at a lower collection temperature. Since the major cost of most solar energy systems is in the collectors, it is important to keep both the unit cost of the collectors and the total amount of collector surface as small as possible.

TABLE 11-3 Collection Efficiencies for Flat-Plate Collectors

Type	Day-long efficiency
Plastic tube type	25%
Bare plate	30%
Covered plate	35%
Suspended plate	40%
2-cover suspended plate	45%

Ordinarily, a surface that is a good absorber is also a good emitter. Collector efficiency can be improved by the use of a selective surface, one which has a high absorption for sunlight but a low radiation emittance. Selective surfaces are usually prepared by a plating on deposition process. At a fixed collector temperature, collector efficiency may be more than doubled over that of an ordinary surface when selective surfaces are utilized. Selective surfaces also permit the collection of energy at a higher than normal temperature without

as large a decrease in collector efficiency as would occur for a nonselective absorber surface.

Table 11-3 presents collection efficiencies for flat-plate collectors.

11.3.5 Heating with Solar Energy

Today, we are able to harness to power of the sun in numerous ways, including using it for water heating, space heating, and space cooling in buildings. Many buildings are now designed to take full advantage of the sun's warmth, and incorporating solar heating in a building will begin to return on the investment immediately. Solar heating can be fully integrated into a building during the design phase or an existing building can be retrofitted to take advantage of solar heating. Solar heating can be used to provide hot water or heat the air in a building (space heating). Solar heating can be either passive, such as simply using large windows to let in more light and warmth, or active, where specially designed mechanical systems increase the heat gained from the sunlight.

Passive Solar Heating. Just as the name implies, passive solar heating allows the sun to do all the work. That is, there is no additional mechanical assistance. When referring to space heating, passive solar design takes advantage of the sun's warmth through such design features as large, south-facing windows and materials in the floors or walls that will absorb warmth during the day and release that warmth at night, when the heat is most needed because the south side of a building always receives the most sunlight. Passive solar water heating refers to a hot water system that is not aided by heat pumps. These systems will include a solar collector to heat the water and a storage tank to store the hot water.

Active Solar Heating. Active solar heating uses concepts similar to passive solar heating. However, active solar takes the power of the sun and amplifies it. Using specially designed mechanical systems, active solar heating can generate much more heat for space heating and hot water than passive solar alone. There are two basic types of active solar heating systems, depending on whether air or a liquid is heated in the solar collector. A liquid-based system heats water or an antifreeze solution in a "hydronic" collector, and an air-based system heats air in an "air" collector. Both of these systems collect and absorb solar radiation, then transfer the solar heat directly to the interior space or to a storage system; an auxiliary or backup system provides the additional heat.

The technical potential for residential applications of solar heating systems is 0.5 to 1.0 m² of solar collector/inhabitant. "Solar countries" such as Israel, Greece, and Cyprus already have high "solar water heating penetration" (Israel has about 0.95 m² per inhabitant), whereas some of the best IEA (International Energy Agency) countries, such as Greece and Austria, have a penetration of between 0.2 and 0.25 m² per inhabitant. The average solar penetration in IEA countries is roughly 0.04 m² per inhabitant; this would suggest that a strong growth of solar heating installations could be expected in the future. Driving forces for market development will be reduced costs and the desire to reduce greenhouse gas emissions. A number of studies carried out by the IEA and the European Commission in several countries reach a common conclusion: the market for solar water heaters is huge and—taken as a whole—is steadily growing, although the market growth will differ widely from country to country. Currently, the most important solar application is for residential water heating. Today, systems for hot water production in single-family houses are dominant; although, in the future, solar heating systems will be used in all types of housing. In countries with centralized heating

systems, such as district heating, large-scale solar energy systems will feed heat to the distribution network. Such systems have been successfully demonstrated in Scandinavia and Germany. Swimming pool solar systems, common in some countries, also present a large market.

11.3.6 Solar Thermal-Conversion Plants

The thermal energy collected from a solar collector can be converted into work or mechanical energy by the use of a heat engine, which can then be used to generate electricity. The three types of thermodynamic cycles which seem to be practical with solar systems are the Rankine cycle, the Brayton cycle, and the Sterling cycle. The *Rankine cycle* is a vapor power cycle that is used with modifications in most large-sized electric generating plants. The *Brayton cycle* is a gas power cycle used as the basis of most gas-turbine power plants. The *Sterling cycle* is a high-efficiency cycle used as the basis for an external combustion gas engine with relatively low pollution and noise characteristics. A schematic flow diagram for a solar power plant operating on the Rankine cycle is shown in Fig. 11-3.

The limitations imposed by the second law of thermodynamics apply to any solar thermal power cycle. This limitation is best expressed in terms of the Carnot principle, which says that it is impossible to construct an engine that operates between two given heat reservoirs and which has a higher thermal efficiency than a Carnot engine operating between the same reservoirs. The *Carnot engine* is an idealized heat engine that is thermodynamically reversible and receives heat from a high-temperature reservoir (the source) and rejects heat to a lower-temperature reservoir (the sink). The useful work done per cycle is the difference between the heat added and the heat rejected during the cycle.

The thermal efficiency, the ratio of useful work done to the heat supplied, is expressed for the Carnot cycle in terms of the temperature of the reservoirs with which it is exchanging heat.

$$\eta = 1 - \frac{T_L}{T_H} \quad (11-5)$$

where η = thermal efficiency of the Carnot cycle

T_L = absolute temperature (degrees Celsius + 273.15°C) of sink

T_H = absolute temperature of source

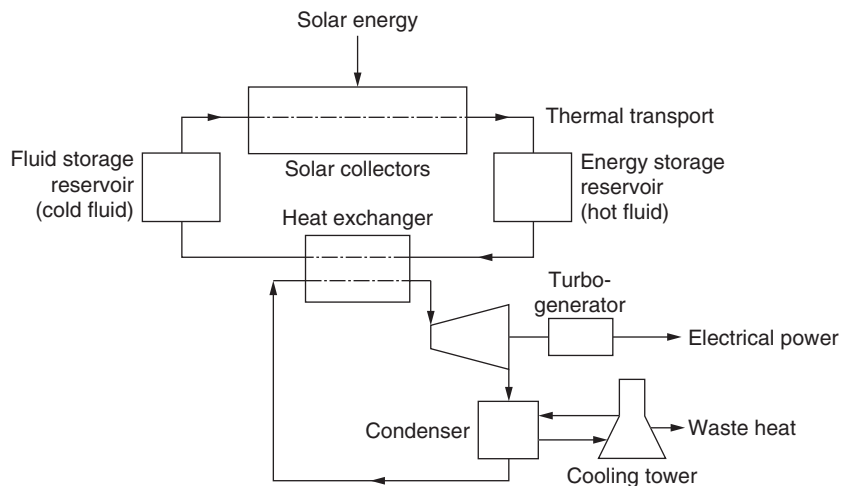


FIGURE 11-3 Schematic diagram of a solar power plant operating on the Rankine cycle.

For a solar energy system collecting heat at 121.1°C (250°F), the maximum thermal efficiency for any heat engine using that heat and rejecting heat to the atmosphere at 10°C (50°F) would be

$$\eta = 1 - \frac{273.15 + 10}{273.15 + 121.1} = 0.282 \quad (11-6)$$

In other words, even an ideal heat engine would convert only 28% of the solar energy collected if the collector exit temperature were 121.1°C (250°F). A real engine would convert considerably less.

The White Paper of the European Commission for a community strategy and action plan on renewable energies of 1997 foresees at least 1 GWe of those systems implemented in Europe by the year 2010. This objective can be achieved by a scenario of a number of 25 to 30 commercial solar thermal power plants with 30 to 50 MWe unit size each and distributed along the south of Europe.

India, Egypt, Morocco, and Mexico have now applied within the GEF (Global Environment Facility) Operational Programme for about U.S. \$50 million GEF grant for each project to cover their incremental costs of solar thermal power projects.

With positive experiences in construction and operation of the first European demonstration power plant projects being under development (50 MWe THESEUS on the Crete island in Greece; 10 MWe Planta Solar [PS 10] in Southern Spain), other projects are expected to follow. Until the year 2015, the market potential for solar thermal power plants is estimated at least with 7 GWe in Southern Europe, representing a CO₂ reduction potential of up to 12 million tons per year.

11.3.7 Concentrating Collectors

Flat-plate collectors have very poor collector efficiencies at temperatures above 93.3°C (200°F), and therefore are not suitable for use in solar thermal power plants. Collectors that concentrate the sun's rays can give higher collector efficiencies and much higher outlet temperatures than flat-plate collectors.

Concentrating collectors use mirrored surfaces to concentrate the sun's energy on an absorber called a *receiver*. The mirrored surface focuses sunlight collected over a large area onto a smaller absorber area to achieve high temperatures.

These collectors reach much higher temperatures than flat-plate collectors. However, concentrators can only focus on direct solar radiation, so their performance is poor on hazy or cloudy days. Concentrators are most practical in areas of high exposure to the sun's rays.

Concentrators are used mostly in commercial applications because they are expensive. Some residential solar energy systems use parabolic-trough concentrating systems. These installations can provide hot water, space heating, and water purification.

11.3.8 Central and Distributed Systems

Solar thermal power plants may be classified as central receiver systems or as distributed systems. In the central receiver system, solar energy is transferred optically from the individual collectors to a single receiver, for example, a boiler for a Rankine-cycle-type power plant. The most common approach for this type of plant is to locate the boiler at the top of a tall tower and to surround the tower with hundreds of mirrors which can reflect the sun's rays to the top of the tower. Systems have been proposed that would generate superheated steam at about 537.7°C (1,000°F) to reach thermal efficiencies comparable with conventional fossil-fueled power plants. The turbine generator would be located on the ground near the base of the tower.

In a distributed system, energy is transported from individual solar collectors by heated fluid flowing through pipes to a central boiler. The collectors are normally of the concentrating type such as parabolic, troughs, or paraboloidal dishes. Flat-plate collectors could be used, but the relatively low temperatures which they can produce lead to low thermal efficiencies. The resulting low overall plant efficiencies would require some rather large areas if flat-plate collectors were used. This is balanced to some degree by the lower cost per unit area of flat-plate collectors as compared with concentrating collectors.

Because of the intermittent nature of the sun, a solar power plant should be operated as an energy-displacement system, in connection with a conventional power system, which is employed whenever

sufficient solar energy is not available because of clouds or night. Another approach is to have fossil fuel available to the solar system to furnish the required heat as needed. A third approach is to store thermal energy collected by the solar system for use during the periods of inadequate solar insulation. In a solar power plant this would involve the storage of a liquid at high temperature. A suitable storage medium should be low in cost and have high heat capacity, high temperature capability, and a lower vapor pressure. It also should be noncorrosive, nontoxic, and have a high thermal conductivity so that heat can be stored or removed at the desired rate without excess heat-transfer surface. If the fluid is to circulate through the solar collectors, it is also desirable that it does not freeze at the temperatures that might be encountered at night. Thermal insulation of the storage tanks is necessary, since storage will be at high temperatures and for reasonably long periods of time. Energy storage also could be accomplished by generating electricity and then using the electricity for pumped storage, electrolysis of hydrogen, charging of batteries, or flywheels.

11.3.9 Solar Energy Facts

In the United States. The position taken by the U.S. government in the current National Energy Review and the ability for the solar industry to structure long-term contracts will be key factors influencing the period over which solar energy takes to become economically self-sustaining. Proposals for a 10% federal tax credit up to \$2,000 per solar system are under review.

Around 1.2 million solar thermal systems have been installed in the United States. Over 80% of these have been to residential users.

On June 10, 2001, Governor George Pataki of New York mandated that state facilities purchase at least 10% of their power needs from renewable sources by 2005, and 20% of those needs by 2010.

On May 16, 2001, the California Energy Commission increased the rebate on solar energy systems to the lesser of 50% off the purchase price or \$4,500 per kilowatt (peak). Previous rebates based on levels as high as \$3,000 per kilowatt (peak).

In Japan. For the fiscal year 2001, the Japanese solar rooftop program received applications for 114 MW of solar from 29,389 households.

Nearly 45% of the world's solar cell production is manufactured in Japan. Japan and the United States are the two biggest exporters of photovoltaic (PV) cells and modules.

Solar capacity is expected to increase nearly tenfold by 2010, which would then account for 30% of renewable energy supply. The national target is 5,000 MW of installed PV systems by the fiscal year 2010.

In Germany. The "Feed-in Law" in Germany permits customers to receive up to 45.7 eurocents per kilowatt hour for solar generated electricity. The program now calls for a total of 1,000 MW to be installed. By the end of 2001, the Kreditanstalt für Wiederaufbau (KfW) Bank, which administers the 100,000 Roof Program in Germany, had approved loans for over 126 MW of PV systems. Bavaria tops the list of states in Germany with over 50 MW of systems approved.

The Feed-in Law fixes tariffs for approved renewable energy projects for a 20-year period from the plant commissioning and will apply incremental price cuts. Initial prices were set at 47.7 cents per kilowatt hour for solar energy, 8.6 cents per kilowatt hour for wind, from 9.6 to 8.2 cents per kilowatt hour for biomass, 8.4 to 6.7 cents per kilowatt hour for geothermal, and 7.2 to 6.3 cents per kilowatt hour for hydropower, waste, and sewage gas.

Some 20,000 solar electricity systems yielding an output of about 77 MW were installed in 2001, almost twice as many as the previous year. With these additions, the total solar electricity capacity in Germany is now estimated at over 170 MW.

According to current estimates, the German solar market reached a volume of about 1.5 billion marks in the year 2000. By the end of the decade, the market volume should increase to almost 7 billion marks.

In Australia. Renewable energy consumed as a percentage of the total energy consumed fell slightly between 1977 to 1978 and 1997 to 1998 (from 7% to 6% of primary energy consumed). Of this 0.9% was solar.

Worldwide. Solar energy accounts for less than 0.1% of the total global primary energy demand. Solar energy demand has grown at about 25% per annum over the past 15 years. (Hydrocarbon energy demand typically grows between 0% and 2% per annum.)

Japan, Germany, and the United States constituted 71% of the world market, unchanged on the previous year. In Japan and Germany, grid-connected applications accounted for over 95% of the market.

For the fiscal year 2002, the Japanese solar rooftop program received applications from 42,838 households.

Over 45% of the world's solar cell production is manufactured in Japan. Europe is second with 25% and the United States with 19%. Around 70% of the U.S. production is exported. However, this percentage will decline over the medium term.

Four companies account for over 50% of solar cell production: Sharp, Kyocera, BP Solar, and Shell Solar.

A residential solar energy system typically costs about \$8 to \$10 per watt. Where government incentive programs exist, together with lower prices secured through volume purchases, installed costs as low as \$3 to \$4 per watt or some 10 to 12 cents per kilowatt hour can be achieved. Without incentive programs, solar energy costs (in an average sunny climate) range between 22 and 40 cents per kilowatt hour for very large PV systems.

Japan overtook Switzerland in 2001 in terms of the proportion of solar cells installed per person in the country.

11.4 PHOTOVOLTAICS

BY AHMED ZOBAA

Solar electric or PV systems convert some of the energy in sunlight directly into electricity. PV cells are made primarily of silicon, the second most abundant element in the earth's crust and the same semiconductor material used for computers. When the silicon is combined with one or more other materials, it exhibits unique electrical properties in the presence of sunlight. Electrons are excited by the light and move through the silicon. This is known as the *photovoltaic effect* and results in dc electricity. PV modules have no moving parts, are virtually maintenance-free, and have a working life of 20 to 30 years.

There are three basic categories of PV systems with several types in each category. Crystalline silicon flat-plate collectors are the most developed and prevalent type in use today. These include single-crystal silicon and polycrystalline silicon, which are either grown or cast from molten silicon and later sliced into their cell size. They are then assembled onto a flat surface; no lenses are used. Thin-film systems are inherently cheaper to produce than crystalline silicon but are not as efficient. They are produced by depositing a thin layer of PV material to a substrate such as glass or metal. This group includes amorphous silicon, like the kind found in calculators and watches. Concentrators use much less of a specialized PV material and employ a lens or reflectors to concentrate sunlight on the PV cell and increase its output. They can be produced more cheaply than either of the other type due to the reduced amount of expensive PV material. However, they can use only direct sun, so they must track the sun precisely and do not work when it is cloudy.

11.4.1 Photovoltaic System Terms

PV system terms progress from small to large as follows:

- PV cells, the smallest unit of a PV system, are wired together to form modules.
- *Modules* are usually a sealed or encapsulated unit of convenient size for handling.
- Modules are wired together to form panels.
- Groups of panels form arrays.

- A number of arrays form an array field.
- The total system includes the arrays and any other equipment, such as charge controllers, storage (batteries), tracking, and monitoring equipment, collectively called *balance of system (BOS) components*.

11.4.2 History of Photovoltaics

The history of photovoltaics dates back to 1839, and major developments evolved as follows:

- In 1839, Edmund Becquerel, a French physicist, observed the photovoltaic effect.
- In the 1880s, selenium PV cells were built that converted light in the visible spectrum into electricity and were 1% to 2% efficient. Light sensors for cameras are still made from selenium today.
- In the early 1950s, the Czochralski meter was developed for producing highly pure crystalline silicon.
- In 1954, Bell Telephone Laboratories produced a silicon PV cell with a 4 % efficiency and later achieved 11% efficiency.
- In 1958, the U.S. Vanguard space satellite used a small (less than 1-W) array to power its radio.
- The space program has played an important role in the development of photovoltaic ever since.
- During the 1973 to 1974 oil embargo, the U.S. Department of Energy funded the Federal Photovoltaic Utilization Program, resulting in the installation and testing of over 3,100 PV systems, many of which are still in operation today.
- The 1970s through the 1990s have seen a relative disinterest in solar power, with majority ownership of many U.S. PV manufacturers being transferred to German and Japanese interests.
- The Gulf War of 1990 again sparked America's interest in non-fossil fuel energy alternatives.

11.4.3 The PV Power Market

PV systems traditionally have been economical in remote applications. Most common examples include wireless and cellular communications systems, off-grid homes, recreational vehicles and boats, power for offshore oil rigs, and highway sign lighting and call boxes. Water pumping, vaccine refrigeration, and water purification have all been important roles for photovoltaics in developing countries.

Market forces seem to have a hold of the PV market, since sales in 1995 rose 20%. Most U.S. manufacturers are increasing production significantly, and costs are expected to fall with the new volumes.

Current estimates of worldwide production of solar photovoltaic cells and modules for 1998 are about 120 MW, up steadily and dramatically from only 40 MW in 1990. Worldwide sales have been increasing at an average rate of about 15% every year during the last decade, although that growth rate has been slower in some markets and regions but faster in others. We believe that there is a realistic possibility for the market to continue to grow at about a 15% rate into the next decade. At this rate, the world production capacity would be 1,000 MW by 2010, and photovoltaics could be a \$5 billion industry. These are realistic benchmarks, and show the solar business to be a very exciting market opportunity in the near term.

Developing countries today are the largest and fastest growing segment of the PV market. For the 2,000 million people in the developing world who currently have no access to basic electrical services, PV presents the opportunity for a giant leap forward and a much needed improvement in living standards. For the PV services industry, the developing world represents an enormous new business opportunity.

Photovoltaic prices are continuing a downward trend as manufacturers increase production. Cost decreases, combined with national and state incentive and subsidy programs, and renewable energy capacity mandates, have led to the emergence of a steadily growing market for bulk photovoltaic installations (greater than 100 kW capacity). Merchant PV plants are being built in places where

favorable feed-in tariffs make projects profitable. Bulk installations significantly decrease the installed cost of PV power at individual sites, while simultaneously driving market demand for PV equipment. The major players and PV technologies in each market are identified along with the mounting modes (roofing tiles, weather skins, carport shading, window walls, and so on) that are prominent. The potential impact of mass production of promising emerging PV technologies is examined. Market forecasts are provided for capacity, new projects, and annual revenue for the 2002 to 2008 time frame. The forecasts cover national, regional, and world markets for both single-site bulk PV installations and bulk purchases for national village power supplies and large residential projects. Project revenue is growing at over 40% per year, and will likely reach \$1 billion annually by 2010.

International Activity. U.S. PV exports increased in capacity from 14.814 million ft² in 1993 to 17.714 million ft² in 1994, an increase of 19.6%. U.S. PV imports increased from 1.767 million ft² in 1993 to 1.98 million ft² in 1994, an increase of 12%. U.S. module production is leading world growth as well. In 1993, the United States produced 21 MW of PV, of which 14.8 MW was exported. By 1997, global demand led to a record breaking PV production year with a 42% leap in worldwide production. The United States produced 46.4 MW with \$175 million in sales and exported 33.8 MW (73% of production) overseas. India is boosting production and becoming a major world producer of PV modules. The Indian government plans to power 100,000 villages with renewable energy, primarily PV modules, and install solar-powered telephones in each of the nation's 500,000 villages. Mexico planned to electrify 60,000 villages using photovoltaics by the year 2000. Hospital Bulape (serving 50,000 outpatients per year in Zaire) and several other major hospitals in Zaire depend totally on solar power for everything from x-ray equipment to air conditioning. In Morocco, solar panels are sold in bazaars and open markets, next to carpets and tinware. In San Buenaventura, Guatemala, a local utility has installed PV panels on 42 of the community's 86 homes at one-third the cost of extending power lines into the village. Malta-Solar Power, Ltd. has begun construction of a new PV plant with a maximum production capacity of 3 MW per year. At full production, this plant will be able to produce 40% of all 1995's module production capacity for all developing countries. South African companies are building a PV manufacturing plant near Alexandra township that will serve to electrify 10,000 homes, 600 clinics, and 1,000 schools with solar power. Kenya has electrified 20,000 homes using photovoltaics in the last few years, compared with 17,000 new homes that were hooked up to the central power grid. Siemens Solar in 1995 sold just over 40% of its output in North and South America, nearly 40% to Europe and Africa, and "just under" 20% went to Asia. SSI President Gernot Oswald expects the biggest growth in the next few years to come from Asia. There are over 500,000 homes using PV today in villages around the world for electricity. In Kenya, more rural households receive electricity from PV than from the conventional power grid. The single largest market sector for PV is village power at about 45% of worldwide sales. This is mostly comprised of small home lighting systems and water pumping. Remote industrial applications such as communications are the second largest market segment.

11.4.4 Global PV Market

The fast growing world market for PV greatly reflects the growing rural electrification demand of less developed countries around the world. The global PV market has grown at an average rate of 16% per year over the decade with village power driving demand. The total worldwide PV production in 1980 was only 6.5 MW, and by 1997 this had increased to 126.7 MW.

For many applications, especially remote site and small power applications, PV power is the most cost-effective option available, not to mention its environmental benefits. New PV modules generally retail for about \$5 per peak watt, depending on quantities purchased. Batteries, inverters, and other balance of system components can raise the overall price of a PV system to over \$10 to \$15 per installed watt. PV modules on the market today are guaranteed by manufacturers from 10 to 20 years, while many of these should provide over 30 years of useful life. It is important when designing PV systems to be realistic and flexible, and not to overdesign the system or overestimate energy requirements (e.g., overestimating water-pumping requirements) so as not to have to spend more money than needed. PV conversion efficiencies and manufacturing processes will continue to improve, causing prices to gradually decrease.

PV conversion efficiencies have increased with commercially available modules that are from 12% to 17% efficient, and research laboratory cells demonstrate efficiencies above 34%. A well-designed PV system will operate unattended and requires minimum periodic maintenance, which can result in significant labor savings. PV modules on the market today are guaranteed by the manufacturer from 10 to 25 years and should last well over 30 years. PV conversion efficiencies and manufacturing processes will continue to improve, causing prices to gradually decrease; however, no dramatic overnight price breakthroughs are expected.

11.4.5 Common Photovoltaic Applications

PV is best suited for remote site applications that have small to moderate power requirements, or small power consuming applications even where the grid is in existence. A few power companies are also promoting limited grid-connected PV systems, but the large market for this technology is for stand-alone (off-grid) applications. Some common PV applications are as follows:

Water Pumping. Pumping water is one of the most competitive arenas for PV power since it is simple, reliable, and requires almost no maintenance. Agricultural watering needs are usually greatest during sunnier periods when more water can be pumped with a solar system. PV-powered pumping systems are excellent for small to medium scale pumping needs (e.g., livestock tanks) and rarely exceed applications requiring more than a 2 hp motor. There are thousands of agricultural PV water pumping systems in the field today throughout Texas. PV pumping systems' main advantages are that no fuel is required and little maintenance is needed.

A PV-powered water pumping system is similar to any other pumping system, only the power source is solar energy; PV pumping systems have, as a minimum, a PV array, a motor, and a pump. PV water pumping arrays are fixed mounted or sometimes placed on passive trackers (which use no motors) to increase pumping time and volume. AC and dc motors with centrifugal or displacement pumps are used with PV pumping systems. The most inexpensive PV pumpers cost less than \$1,500, while the large systems can run over \$20,000. Most PV water pumpers rarely exceed 2 hp in size. Well installed quality PV water pumping systems can provide over 20 years of reliable and continuous service.

Gate Openers. Commercially available PV-powered electric gate openers use wireless remote controls that start a motorized actuator that releases a gate latch, opens the gate, and closes the gate behind the vehicle. Gates are designed to stop if resistance is met as a safety mechanism. Units are available that can be used on gates up to 16 ft wide and weighing up to 250 lb. Batteries are charged by small PV modules of only a few watts. Digital keypads are available to allow access with an entry code for persons without a transmitter. Solar-powered gate-opening assemblies with a PV module and transmitter sell for about \$700.

Electric Fences. P-power can be used to electrify fences for livestock and animals. Commercially available packaged units have maintenance free 6 or 12-V sealed gel cell batteries (never need to add water) for day and night operation. These units deliver safe (non-burning) power spikes (shocks) typically in the 8,000 to 12,000 V range. Commercial units are UL (Underwriters Laboratories) rated and can effectively electrify about 25 to 30 miles of fencing. Commercially packaged units are available from about \$150 to \$300, depending on voltage and other features.

Water Tank Deicers. For the north plains of Texas in the winter, PV power can be used to melt ice for livestock tanks, which frees a rancher from going out to the tank with an ax to break the surface ice so the cows can drink the water. The PV module provides power to a small compressor on the tank bottom that generates air bubbles underwater, which rise to the surface of the tank. This movement of the water with the air bubbles melts the tank's surface ice. Commercially available units are recommended for tanks 10 ft in diameter or greater, and can also be used with ponds. Performance is best for tanks that are sheltered, bermed, or insulated. Installation is not recommended for small, unsheltered tanks in extremely cold and windy sites. Approximate cost for a complete owner-installed system, including a PV module, compressor, and mounting pole, is about \$450.

Commercial Lighting. PV-powered lighting systems are reliable and a low-cost alternative widely used throughout the United States. Security, billboard sign, area, and outdoor lighting are all viable applications for PV. It's often cheaper to put in a PV lighting system as opposed to installing a grid lighting system that requires a new transformer, trenching across parking lots, etc. Most stand-alone PV lighting systems operate at 12 or 24 V dc. Efficient fluorescent or sodium lamps are recommended for their high efficiency of lumens per watt. Batteries are required for PV lighting systems. Deep cycle batteries specifically designed for PV applications should be used for energy storage for lighting systems. Batteries should be located in protective enclosures, and manufacturer's installation and maintenance instructions should be followed. Batteries should be regulated with a quality charge controller. Lighting system prices vary depending on the size; average systems cost from \$600 to \$1,500.

Residential Power. Over 500,000 homes worldwide use PV power as their only source of electricity. In Texas, a residence located more than a mile from the electric grid can install a PV system more inexpensively than extending the electric grid. A Texas residence opting to go solar requires about a 2 kW PV array to meet its energy needs, at a cost of about \$15,000. The first rule with PV is always energy efficiency. A PV system can provide enough power for an energy-efficient refrigerator, lights, television, stereo, and other common household appliances.

A great number of PV installations for homes have taken place in Mexico. The experience of PV electrification varies widely across Mexico and is demonstrative of the potential pitfalls of haphazard installations. Over 40,000 PV home lighting systems have been installed in Mexico, mostly through government programs (Foster 1998). However, nearly half of these systems are not functioning today, mostly due to poor balance of systems hardware (i.e., the PV modules work fine), where improper batteries and poor quality charge controllers are used. It is important for any PV user to use quality equipment and install PV systems in accordance with local electric codes. This greatly reduces the potential for future problems.

Evaporative Cooling. PV-powered packaged evaporative cooling units are commercially available and take advantage of the natural relation that when maximum cooling is required is when maximum solar energy is available. These units are most appropriate for comfort cooling in the dry climate of West Texas where performance is best. Direct evaporative coolers save 70% of the energy over refrigerated units. Battery storage is obviously required if cooler operation is desired at night. Array size would vary with the power requirements of the cooler motor. A linear current booster (LCB) is useful between the PV modules and the cooler's dc motor if the cooler is coupled directly to the PV array. Packaged PV evaporative cooling systems for residences generally run from \$500 to \$1,500, depending on size.

Telecommunications. This was one of the early important markets for PV technologies, and continues to be an important market. Isolated mountaintops and other rural areas are ideal for stand-alone PV systems where maintenance and power accessibility make PV the ideal technology. These are often large systems, sometimes placed in hybrid applications with propane or other type of generators.

Consumer Electronics. Consumer electronics that have low power requirements are one of the most common uses for PV technologies today. Solar-powered watches, calculators, and cameras are all everyday applications for PV technologies. Typically, these applications use amorphous PV technologies that work well even in artificial light environments such as offices and classrooms.

11.4.6 Glossary of Solar and Photovoltaic Terms

Cell Efficiency. The ratio of the electrical energy produced by a PV cell (under full sun conditions or 1 kW/m^2) to the energy from sunlight falling on the cell.

Charge Controller. A component that controls the flow of current to and from the battery subsystem to protect the batteries from overcharge and overdischarge. The charge controller also may monitor system performance and provide system protection.

Diffuse Radiation. Sunlight received indirectly as a result of scattering due to clouds, fog, haze, dust, or other substances in the atmosphere.

Direct Radiation. Light that has traveled in a straight path from the sun (also referred to as beam radiation). An object in the path of direct radiation casts a shadow on a clear day.

Flat-Plate Array. A photovoltaic array in which the incident solar radiation strikes a flat surface and no concentration of sunlight is involved.

Fresnel Lens. A concentrating lens positioned above and concave to a PV material to concentrate light on the material.

Grid-Connected. Referring to an energy-producing system connected to the utility transmission grid (also called utility interactive).

Hybrid System. A power system consisting of two or more power-generating subsystems (e.g., the combination of a wind turbine and a PV system).

Insolation. The amount of sunlight reaching an area usually expressed in watts per day.

Load. Electrical power being consumed at any given moment. The load that an electrical generating system supplies varies greatly with time of day and to some extent season of year. Also in an electrical circuit, the load is any device or appliance that uses power.

Parallel-Connected. Referring to a method of connection in which positive terminals are connected together and negative terminals are connected together. Current output adds and voltage remains the same. (See also series-connected.)

Photovoltaic Cell. The semiconductor device that converts light into dc electricity. The building block of PV modules.

Series-Connected. Referring to a method of connection in which the positive terminal of one device is connected to the negative terminal of another. The voltages add and the current is limited to the least of any device in the string. (See also parallel-connected.)

Solar Constant. The rate at which energy is received from the sun just outside the earth's atmosphere on a surface perpendicular to the sun's rays. Approximately equal to 1.36 kW/m².

Thick Cells. Conventional cells, such as crystalline silicon cells, which are typically from 4 to 17 mil thick. In contrast thin-film cells are several micrometers thick.

Thin-Film Cells. PV cells made from a number of layers of photosensitive materials. These layers are typically applied using a chemical vapor deposition process in the presence of an electric field.

Voltage Regulator. A device that controls the operating voltage of a PV array.

11.5 WIND POWER

BY PALMER CARLIN

11.5.1 Introduction

In order to present the current status of wind energy technology concisely but still include important related issues, the following material is divided into four sections: the first section provides a quick

survey of contemporary activity in wind energy. The second section presents the basic physics and technology of wind energy conversion together with a description of turbine features. The third section includes issues that arise in the application of wind machines, and the fourth and final section contains conclusions and references.

11.5.2 Contemporary Activity in the Wind Energy Field

With the onset of the energy crisis in 1976, interest in renewable energy sources suddenly intensified. As a result, both private and government agencies became involved. As an example of private activity, the American Wind Energy Association (AWEA) was founded with provision for both corporate and individual memberships. Typical corporate members are electric utilities and wind turbine manufacturers, while typical individual members are wind consultants, university personnel, wind turbine owners, and private citizens. A directory of its membership is available on the Internet.¹

The U. S. Department of Energy (DOE), working through the National Wind Technology Center (NWTC) of the National Renewable Energy Laboratory (NREL) in Golden, Colo., supports a comprehensive wind energy program. Sandia National Laboratories (SNL) in Albuquerque, New Mexico, participates in the national program as well. One part of the program offers cost-shared contracts to private industry on a competitive basis for the development of advanced wind technology. Other parts of the program support wind research within the government laboratories, and the testing facilities at the NWTC can be made available for qualifying private companies.

In anticipation of the rising global importance of wind energy, in 1977 the International Energy Agency launched the Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems.² Since then, 19 nations have joined this group by becoming members of its executive committee, which meets semiannually to exchange information about wind energy developments. The location of the meeting rotates among member nations, and the hosting nation includes visits to its wind installations. As wind technology progresses and new challenges arise, the committee creates suborganizations called *annexes* to which member countries contribute expert delegates. The operating agent of each annex reports to the executive committee at its semiannual meetings until the annex completes its task. In their 2004 Annual Report, the executive committee stated that the world's wind generation capacity exceeded 47 GW and was expected to continue growing at a rate of 28% per year.

11.5.3 Wind Turbine Analysis and Description

Wind Turbine Power Calculation. Good engineering models for predicting wind turbine performance can be obtained from some simple assumptions plus a few equations from elementary physics. By considering energy, momentum, and mass conservation laws, aerodynamicists in the mid-nineteenth century established the "axial momentum" theory for analysis of airplane propellers. One of the results is the expression for the flux of kinetic energy of the wind or any other fluid through an area normal to that fluid flow, which is

$$P_w = \frac{1}{2} \rho A V_w^3 \quad (11-7)$$

where P_w is total wind power in watts, ρ is air density in kilograms per cubic meter, A is a mathematical area in square meters normal to the wind, and V_w is the wind speed passing through that area in meters per second. The cubed velocity is plausible because each air mass element carries kinetic energy proportional to velocity squared, and the rate of passage of each element being directly proportional to velocity yields the third velocity factor.

Because the extractable energy of the wind exists only as macroscopic kinetic energy, no practical machine can remove all of that energy, as there is no way to dispose of the resulting stationary air. Two aeronautical engineers independently examined this limitation in the 1920s. Lanchester³ and Betz⁴ separately used the ideal model in Fig. 11-4. It assumes that the perfectly inviscid fluid passes through an "actuator disc," which represents a wind machine rotor. An *actuator disc* is a mathematical convenience commonly used in wind turbine (as well as aircraft propeller) analysis. This porous disc extracts

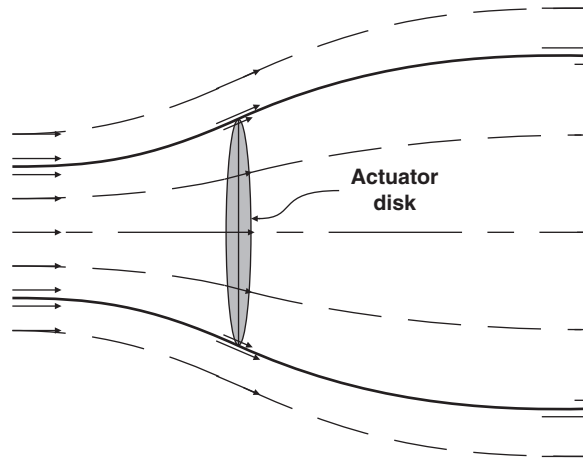


FIGURE 11-4 Idealized inviscid fluid flows through an actuator disk.

mechanical energy from the flow by causing a pressure drop. On the upstream side, the pressure has been raised above atmospheric by the slowing airstream, while on the downstream side pressure is lower. Ambient atmospheric pressure in the flow will be recovered downstream by further slowing. By extending axial momentum theory to this model, they showed that the maximum fraction of the above wind power that can be captured is $16/27$ or about 59%. This is known as the *Lanchester/Betz Limit* or more commonly the *Betz Limit*. Mathematical results derived using this model are assumed to apply as an upper limit to any device that extracts kinetic energy from a free fluid stream.

To account for this fundamental limit as well as additional imperfections introduced by practical wind turbines, wind engineers define the dimensionless power coefficient, C_p , for a wind turbine as follows

$$P = \frac{1}{2} \rho A C_p V_w^3 \quad \text{watts} \quad (11-8)$$

where P is now the useful extracted power. One can see that this coefficient for a particular machine is the fraction of the total wind power that the wind machine can reclaim in a wind of V_w . Depending on the context this power may or may not include the losses in the power train of the turbine. Because of the Betz limit this fraction can never exceed 0.59. Measured values of power coefficient for real turbines range from 0.25 to more than 0.45.

There are a few important additional observations to be made in Fig. 11-4. First, note that the wind speed in the tube of air that will impinge on the disc (bounded by solid lines) begins to slow before it arrives there and it continues to slow after it leaves. As this fluid is assumed ideal, it has no viscosity, so the surrounding air slides past the subject tube and neither speed is affected by the other.

Second, for the mass flow to remain constant at any cross section, the declining fluid speed requires the tube cross section to expand. The velocity reduction and, therefore, the change in flow cross section proceeding from left to right, depends on the amount of energy being removed from the flow. Note that these results are independent of the type of device that is extracting energy from the flow. In the limit of no removal, the fluid tube cross section remains constant and equal to that of the actuator disc, and there would be no reduction of wind speed.

Finally, the velocity vectors shown represent the optimal case of the Betz limit. For this case, the impinging wind speed has been reduced to two-third of its original value as it reaches the turbine disc, and ultimately declines to one-third of the original value downstream. In this ideal case, the velocity reduction for this tube of fluid is permanent as mentioned above. In real cases of viscous flow in the atmosphere, this wake is dissipated and reenergized downstream by the surrounding untarried wind. This wake process is very important to the design of a wind power plant with many

successive rows of turbines. Turbines positioned farther into the center of a wind power plant are subjected to much greater turbulent buffeting that results in blade fatigue and up to 15% loss of annual energy compared to the most upwind turbines.

Obviously, current engineering analyses that account for the rotating blades and the effect of material fatigue are much more refined. For an excellent account of these approaches, consult Ref. 5.

11.5.4 Wind Turbine Classes

Based on the method of extracting energy from the airstream, two fundamental classes of wind machines can be defined. "Lift type" machines use airfoils that create lift at right angles to the air-flow like an airplane wing. On the other hand, if a machine extracts energy by depending on the wind to push a specially shaped object directly downwind, it is a member of the other and much older class of wind machines called "drag machines."

In the lift class of machines, it is convenient to divide turbines into two main classes based on the orientation of their axis of rotation. The rotor axis of the horizontal axis wind turbine (HAWT) is parallel to the flow of the wind, while the rotor axis of the vertical axis wind turbine (VAWT) is transverse to the wind. At this writing, the latter constitutes less than 3% of commercial wind machine installations.

Horizontal Axis Wind Turbine. Usually, the designer of a new wind machine will select the power rating and the axis orientation first. For a HAWT at least four other important choices follow:

Rotor Orientation. In an upwind HAWT, the wind passes through the rotor before passing the tower, so that the blades are never shielded from the direct wind. However, special mechanical drives with control systems and direction sensors must be provided to move (yaw) and maintain the rotor in this upwind position. Conversely, a downwind machine can depend on the natural tendency of the wind to blow the rotor to the opposite side of the tower, and thus preclude the need for the special mechanical drive and sensors. The cost, however, is that each blade must pass through the turbulent wind region behind the tower, and thereby experience mechanical impulses that can shorten the rotor's fatigue life and create additional noise.

Blade Count. Although multiple-bladed turbines exist, economic factors at least for the present, have determined that either two- or three-bladed rotors are the most practical. It should be mentioned that the moment of inertia of a three-bladed rotor about its yaw axis is independent of the rotor's position, while this quantity varies from a maximum to a minimum as a two-bladed rotor rotates from horizontal to vertical orientation. During high yawing rates, this means that the gyroscopic moment on the main shaft is fluctuating wildly for a two-bladed rotor (See Hub Type).

Hub Type. The simplest and most obvious case of blade attachment is the rigid hub in which there is no relative motion of the rotor blades with respect to the supporting shaft. This is the usual case for smaller three-bladed rotors and is often used for two blades. Alternatively, suppose the wind machine rotor uses only two blades built as a long rigid beam, and suppose these blades are attached to the wind machine's main drive shaft by a single pin transverse to both this shaft and the blades. If this pin acts as a hinge allowing a small amount of movement, then this is a "teetering rotor." This feature eliminates bending at the end of the main rotor shaft in a turbulent wind and allows the plane of rotation of the blades to be somewhat misaligned with the main rotor shaft of the turbine for a few moments if necessary.

Aerodynamic Control. In considering aerodynamic control, we must distinguish between the control of power flow and the need to stop rotation in case of equipment failure or excessive wind. Although the speed of a wind turbine is normally controlled by the load torque of its electric generator, excess wind, loss of utility power, breakdown of the generator, or loss of the mechanical transmission would allow the turbine rotor to spin out of control. For this reason, all wind machines need some form of aerodynamic control.

The two most common hardware approaches to meeting this problem are (1) stall control and (2) pitchable blades. If stall control is chosen, the turbine will be designed such that when the wind exceeds the speed that fully loads the generator, the resulting large angle of attack of the wind on the blade airfoil causes the blades to stall thereby reducing mechanical power to the generator shaft.

In this case, the wind machine rotor blades are mounted permanently at a fixed pitch angle. The appeal of this method is its simplicity and consequent lower cost.

Alternatively, the existence of pitch control on propeller driven aircraft suggests full-span pitch control for wind machines, in which each blade can be rotated around its own longitudinal axis. When the rotation is sufficient to present the leading edge directly into the wind (i.e., approximately 90°), the average wind torque on the rotor will go to zero. Thus, positive control is achieved at the expense of rotating blade root attachments and complicated mechanical hub linkages, but enjoys the advantage (over stall control) of being able to reduce wind torque to zero on average.

Many stall-controlled turbines have additional aerodynamic control for emergencies in the form of tip flaps. These are flat plates mounted at the tip of the wind machine blades and normal to the blade's longitudinal axis. During normal machine operation they are in the stowed position where they present their edge to the slipstream and consequently offer low drag resistance. In case of incipient loss of control, these tip flaps can be deployed either by centrifugal force or by electrical trigger. They then pivot outward, presenting their entire surface broadside to the slipstream. This tangential drag force dramatically reduces rotor speed, though it does not stop the rotor completely. A mechanical brake is provided for that purpose.

Vertical axis wind turbine. The Darrieus or vertical axis wind turbine, which is sometimes called the "eggbeater" type machine, has several important advantages. It will operate with the wind approaching from any direction, the generator can be mounted in the base of the machine, and the primary mechanical loads on the blades are tension. Measured power coefficients are similar to those for HAWT machines. Some disadvantages are that aerodynamic torque only occurs as the blade moves across the wind, which results in torque pulsation, and the turbine is not self-starting. However, the primary problem is that the long slender blades are subject to many different modes of vibration with the resulting loss of fatigue life.

11.5.5 Wind Turbine Performance

Probably the most important quantitative information about a wind turbine is its power curve. A typical example is shown in Fig. 11-5 in which the rotor is assumed to be turning at a constant speed. The ordinate shows the power that a machine will produce if it is being driven by the steady wind shown on the abscissa. This example machine reaches its rated speed and power at about 17 m/s, and its furling or cutout wind speed at 23 m/s at which point its control system will automatically shut it off.

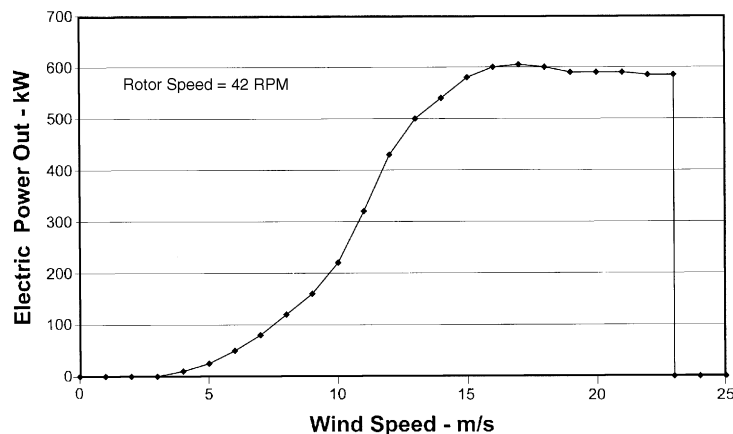


FIGURE 11-5 A typical power curve for a constant speed turbine (rotor speed = 42 rpm).

Although the previous power expression shows that power should be proportional to the cube of the wind speed, typical wind machine power rises more slowly and levels off at higher wind speed. This is because the power coefficient, C_p , is not a constant. To account for the effect of rotor speed on the power coefficient, it is useful to define a dimensionless quantity called “tip-speed ratio” sometimes abbreviated TSR or lambda (λ).

$$\lambda = R\omega/V_w \quad (11-9)$$

where R is the radius of the circle swept by the rotor, ω is the rotor angular speed in radians per second, and V_w is the wind speed. Note that the TSR can be thought of as the linear speed of a rotor blade tip measured in units of the existing wind speed. Thus, for a TSR of 7, the blade tip is traveling 7 times faster than the wind at that instant.

For a wide range of rotor and wind speeds it can be shown that the power coefficient is a function of TSR as is seen in Fig. 11-6. It is therefore possible, by knowing rotor speed and wind speed, to calculate the power produced by the given wind turbine using the expression

$$P = \frac{1}{2} \rho A C_p(\lambda) V_w^3 \quad (11-10)$$

where C_p is obtained from Fig. 11-6. By finding the TSR for maximum C_p , we can calculate the rotor speed for a given wind speed that will give best performance for this machine. It will therefore mark the wind speed neighborhood in which we should strive to operate the machine.

This is discussed further in Sec. 11.5.8.

Figure 11-6 also shows that the power coefficient curve drops to zero for high TSRs. This can be interpreted as the TSR that would be obtained if no load were placed on the wind machine rotor, and the TSR at that point allows us to calculate the “runaway” rotor speed for any given wind. Although this speed is finite, most large machines are not designed to operate at such high speeds and would be damaged or destroyed if they were allowed to do so. On the other hand, for TSRs less than about 3, the power coefficient can be seen to be low and usually not well-known, because most fixed-pitch turbine airfoils will be stalled at this angle of attack.

While the information in Fig. 11-6 is sufficient to approximate the performance of fixed-pitch, constant-speed machines, if blade pitch is available as another control variable, then more information

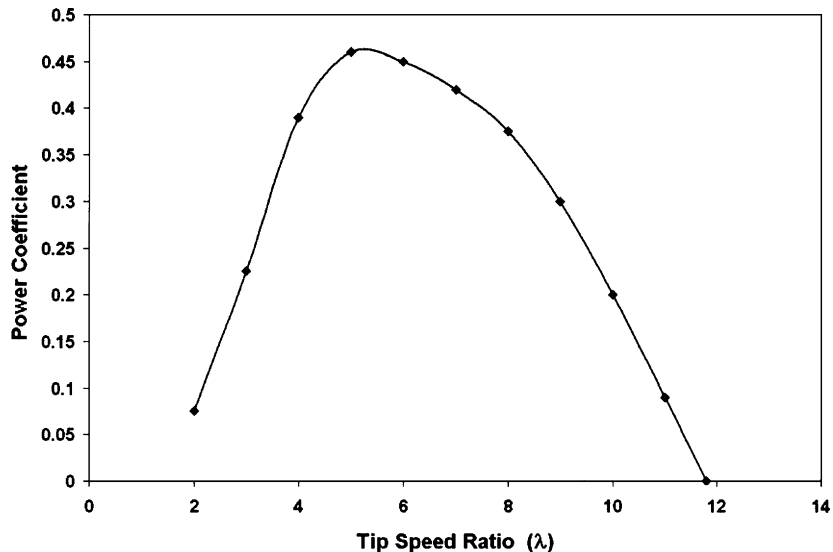


FIGURE 11-6 Example of a power coefficient vs. tip-speed ratio curve.

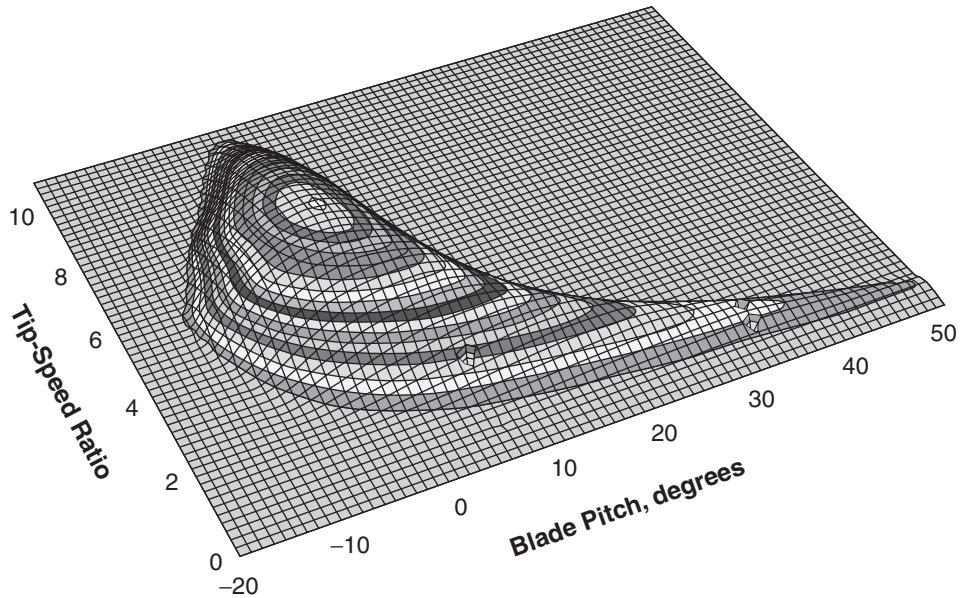


FIGURE 11-7 Power coefficient surface of a typical wind turbine.

is needed. Recall that blade-pitch angle is the angle between a blade chord line and the plane of rotation of the wind machine rotor, and for most high-speed turbines, it is in the range of 0° to 6° .

To account for this new variable, we must resort to a mathematical surface in three-dimensional space. In Fig. 11-7, the power coefficient is shown as a function of both TSR and blade-pitch angle. The fact that this surface has a single C_p maximum near zero degrees pitch and a TSR of 6 shows that maximum performance for this turbine can be had at really only one blade-pitch angle and at one TSR. Thus, ideal performance will occur only if the rotor blade tips are moving about 6 times faster than the existing wind speed and the blades are pitched to approximately zero. Of course, if a wind machine's electrical or mechanical capacities are being exceeded, pitch can be used to reduce power.

Other aerodynamic control techniques that have been tested include pitchable blade tips, ailerons, spoilers, and generator torque.

All of the preceding material applies only to devices that use airfoils that extract energy through the use of aerodynamic lift. The older wind machines that use the drag phenomenon exist in many forms, such as the ubiquitous cup anemometer. Although the latter is useful for accurate wind speed measurement, it is not efficient in the collection of raw energy. Machines using this technology are usually robust and can be fabricated using unsophisticated equipment. However, per unit of active collection area, they tend to require much more material than a lifting machine. But more important is that the maximum theoretical power coefficient for this technology ($C_p = 4/27$) is exactly one-fourth that of the lifting class of wind machine ($C_p = 16/27$). This is the reason that drag machines are never found in commercial wind power plants.

The purpose of this hardware section was limited to a discussion of wind machine energy conversion performance. The complete detailed design of a commercial wind machine would also include an extensive structural loads and fatigue analysis.

11.5.6 The Wind Resource

As indicated in the previous discussion, the wind turbine's energy source, the wind, must be well-known to accurately site turbines and predict performance. The Pacific Northwest National Laboratory (PNNL), at the request of DOE, began studying the wind resource in the United States

and its territories in 1979 to identify practical locations for wind energy exploitation. Today, wind resource activities take place at NREL. In the wind maps developed by PNNL and NREL, the results are presented in terms of wind classes. Class 1 is least energetic while class 7 is the most energetic. An annual average wind resource map for the United States is shown in Fig. 11-8. In the atlas developed by PNNL⁶, wind resource data are sorted in various ways such as by seasonal average, by annual average, by elevation above the terrain, or by land topography. State wind resource maps recently produced by NREL show much greater detail than the national map shown in Fig. 11-8.

The fact that the atmosphere has viscosity and that the lowest layers of the wind are being slowed by contact with the earth's surface means that the wind speed will change according to the altitude above the earth's surface. Although this wind shear depends on many local variables, the commonly accepted empirical expression for this change below about 300 m is a power law:

$$v_2/v_1 = (h_2/h_1)^\alpha \quad (11-11)$$

where α = about a one-seventh average, v_n = wind speeds at vertical locations 1 and 2, and h_n = elevations above a reference plane for 1 and 2.

Although the wind by its nature is stochastic, for a given geographical location, it is possible to assign a characteristic wind speed probability density curve. Such curves, together with power curves for a particular model of wind machine, can be used for good estimations of the annual energy that can be captured and therefore a good estimation of annual revenue from a proposed wind power plant. Because the power that can be extracted from the wind varies as the cube of the instantaneous wind speed, a region having, for example, a 2% higher annual mean wind compared to another region will be expected to yield 6% more energy than the second region, all other things being equal. This difference can be financially important for a wind farm operator.

Many probability expressions have been examined, but present usage has evolved to just a few. For example, a Gaussian curve will usually give a very good fit to a 10-min wind speed data set. However, the Weibull expression is more widely accepted for annual records. Two parameters, c and k , give the Weibull curve its flexibility to more nearly fit experimental data. The c parameter adjusts the numerical scale on the abscissa or independent variable axis. The shape factor, k , adjusts the relative width of the peak of the curve:

$$f(v) = \frac{k}{c} \left(\frac{v}{c} \right)^{(k-1)} e^{-\left(\frac{v}{c}\right)^k} \quad (11-12)$$

Examples of the Weibull function are given in Fig. 11-9 for $k = 2$ and $k = 3$.

Good energy sites for wind machine installations very often can be fit with a shape factor of $k = 2$. This special case of the Weibull expression is the well-known Rayleigh function. A useful theoretical model can be made by postulating a perfect wind machine that can operate in all winds at the Betz limit of power coefficient, namely $0.593 = 16/27$. Assume this machine is placed in a region where the wind statistics exactly fit a Rayleigh probability density function. Calculations based on this model can be used to set upper limits to the amount of annual energy that can be captured by any real machine in a similar location. In particular, if inertia effects are ignored, and the product of this ideal Betz power curve and the Rayleigh function is integrated over all winds, the result will be the mean annual power of a "Rayleigh-Betz" wind machine. It can be reduced to the following expression⁵:

$$P_{av} = \rho (2/3 D)^2 V_{av}^3 \quad (11-13)$$

where ρ is air density, D is the diameter of the swept area, and V_{av} is the mean annual wind. The implied annual energy that this ideal model will collect will therefore be the product of the hours in a year with this average power. For example, if a wind machine with a 15-m rotor diameter is operated at sea level for a year in an ideal Rayleigh wind regime of mean value 5 m/s, then the energy captured could not exceed

$$\begin{aligned} W &= 8,760 \text{ h/year} \times 1.2 \text{ kg/m}^3 \times (2/3 \times 15 \text{ m})^2 \times (5 \text{ m/s})^3 \\ &= 131.4 \times 10^6 \text{ watthours} = 131.4 \text{ megawatthours} \end{aligned}$$

UNITED STATES ANNUAL AVERAGE WIND POWER

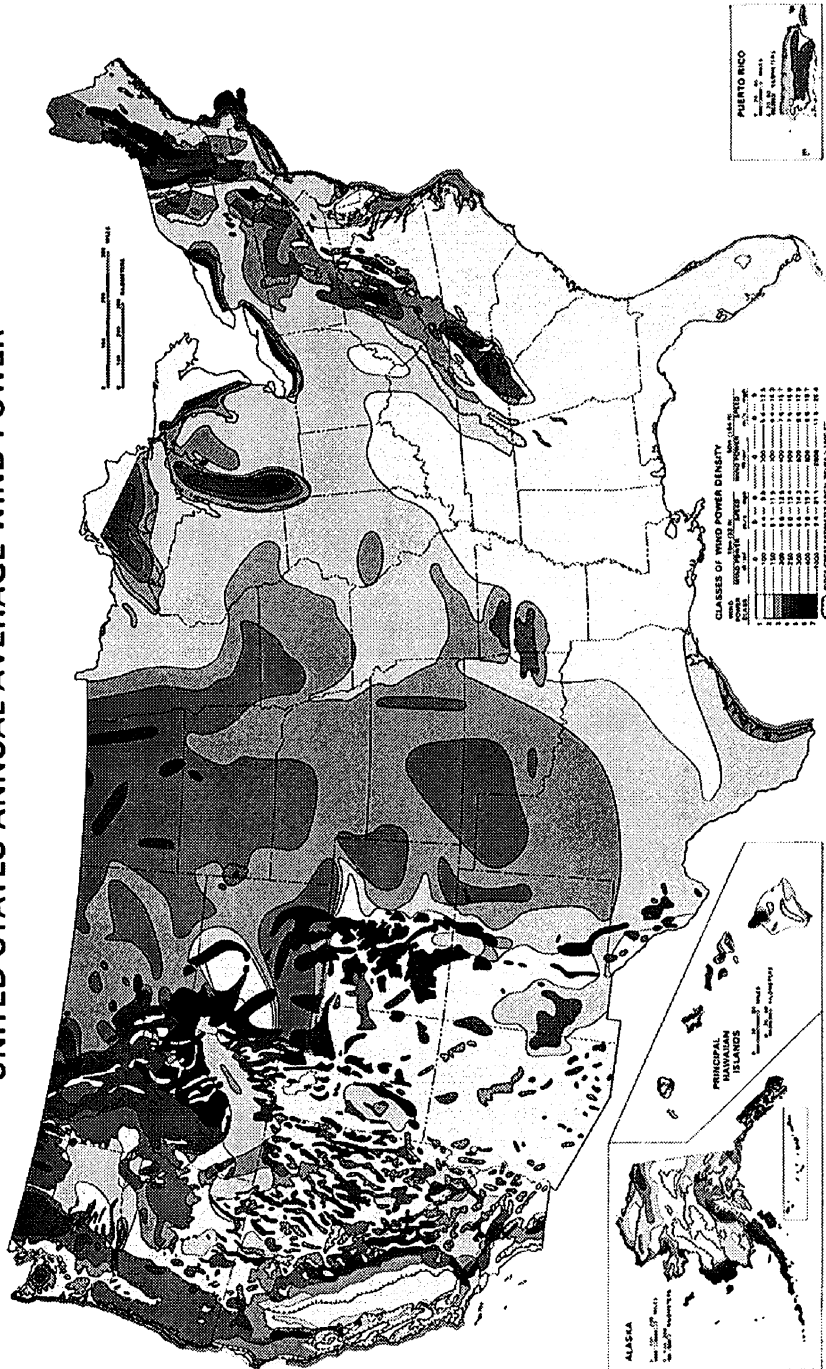


FIGURE 11-8 Wind energy resource map of the United States.

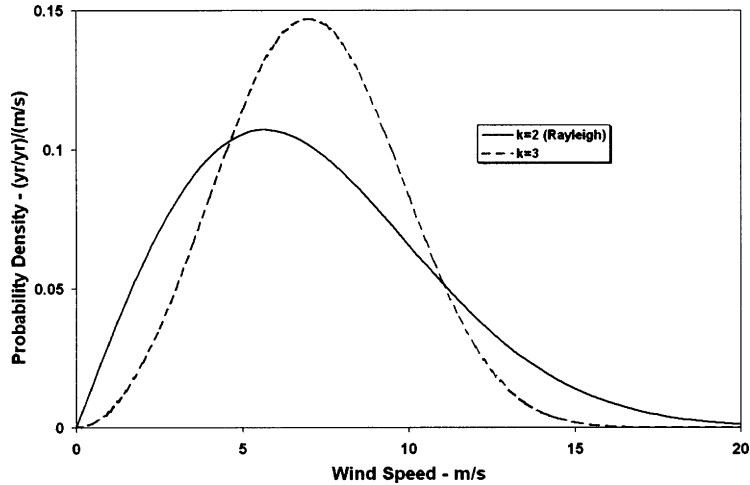


FIGURE 11-9 Weibull probability densities for scale factor $c = 8$ m/s.

Note that average air density has an important influence on calculated wind turbine power, as shown in this example: The sea level air density of 1.2 kg/m^3 falls off to 1.0 kg/m^3 at about 1,500 m above sea level. This of course means a power reduction back to 83% of sea level power for the same wind speed. If seasonal changes in temperature and barometric pressure are known, corrections to annual calculated power can be made.

Being able to estimate annual average wind speeds and annual output is useful for planning purposes, but being able to forecast the wind accurately for one or two days could provide a significant economic benefit, allowing utility engineers to plan ahead for wind generation to replace fossil-fueled generation. Various methods have been developed, and are continuing to be developed, to accurately forecast wind power one to two days ahead. Several commercial companies offer this wind forecasting service.

11.5.7 Wind Turbine Electric Systems

Generators. During the rapid development of wind power plants in the late 1980s and early 1990s, nearly all grid-connected wind turbine generators were of the induction type. Induction generators are much less expensive than the synchronous type, but their primary flaw is their need to draw lagging current from the grid to supply their excitation. This apparent disadvantage is sometimes useful for a utility in that if the utility to which they are paralleled goes down, induction generators lose their reactive excitation from the utility grid and automatically cease producing power. Presumably, aerodynamic controls on the wind turbine rotor will limit its speed if it loses its load in this manner.

It has become commonplace for electric utilities to require induction generator owners to provide power factor correction capacitors that will supply nearly all of the required lagging current. The flaw of this solution is that if the interconnected utility were to have a forced outage, there is the possibility for self-excitation of the remaining online wind generators. Thus, if this isolated subsystem happens to have generation approximately equal to its load, then the system could sustain itself long enough to cause considerable damage. At present, this scenario is essentially impossible because of the wind turbine's control system, which halts the turbine if either frequency or voltage stray beyond given narrow limits.

At present, a growing electric generator technology receiving consideration for wind systems is the permanent magnet (PM) type. Certain small wind turbine systems in the range of less than 10 kw have employed such generators for many years. Progress in the development of rare earth permanent magnets and other types of permanent magnets has made the use of PM generators more feasible for

larger-sized wind systems. The advantages of PMs over conventional synchronous generators are simplicity of construction and no energy loss in the field winding. These advantages are achieved at the price of no adjustment of field strength and the high cost of permanent magnets. The loss of flexibility in the PM generator can be largely compensated for with semiconductor power processing.

Power Electronics. The continuing progress in the development of larger and less expensive semiconductor devices has opened the way to variable-speed, constant-frequency wind energy systems. The rapid growth of the use of adjustable speed drives for motors in manufacturing production lines illustrates the present high reliability of power electronics. The two most frequent methods of using this technology for generation are (1) conversion of the entire variable-voltage, variable-frequency output of a wind machine (sometimes called “wild ac”) to direct current, then reconverting it to utility quality ac power; and (2) alternatively, when a wound rotor, variable-speed induction machine is fed with an appropriate variable frequency current from a power semiconductor system, the stator will supply constant voltage, constant frequency power to the interconnected utility bus. This arrangement is usually called the doubly fed induction generator and offers the advantage of a smaller power rating for the power electronics equipment.

11.5.8 Controls and Control Algorithms

The prime movers for conventional utility grid generators, having been developed along with their companion generators, are capable of very precise speed and power control. These levels are totally under the control of the utility dispatcher.

Wind turbines, however, must exploit whatever wind presents itself at a particular instant. Anemeronomic (wind energy) engineers have agreed on a taxonomy to describe the three successive operating regions that a wind turbine progresses through as the ambient wind increases from calm to maximum. Region one is that region preceding startup and below cut-in. Cut-in is the point at which there is just sufficient wind to produce measurable energy. For most machines this is in the range of 4.5 to 5 m/s.

Region two identifies operation between cut-in and rated power operation; it is where the electrical power output uniformly increases as wind speed rises from cut-in speed. For constant-speed wind turbines in this region, rotor speeds are selected such that the maximum power coefficient will occur when the most productive wind exists. The most productive wind is that speed, which if a wind turbine were allowed to operate only in a narrow band centered on this speed, would capture more energy than being centered on any other narrow band of wind speed. This wind speed exists because of the opposing effects of exploitable energy rising with the cube of wind speed and the decline in frequency of occurrence of such winds for increasing speeds. For the special case of a wind regime governed by the Rayleigh probability density, this wind speed occurs at 159% of the annual average wind and at exactly twice the most probable wind speed. The range of possible values for the wind speed that defines the upper edge of region two is quite broad and is machine dependent. It is usually the least wind that will yield the maximum continuous power output for that turbine.

Variable-speed wind turbines in region two attempt constantly to adjust their speed to hold their TSR at the maximum power coefficient point. This flexibility is purported to make it possible to collect theoretically up to 20% more annual energy than the same machine constrained to operate at constant speed. The obvious consideration is to balance this gain with the expense and power losses in any auxiliary equipment such as power electronics modules that are needed to provide the variable-speed feature.

As steady-state operation in wind speeds beyond rated speed would overheat the generator, means must be taken to limit wind power input. This identifies the upper edge of region two, which is the lower edge of operating region three. It is the region where the control algorithm must change from attempting to maximize energy capture to minimizing equipment damage. Although in principle, generator torque can be used to continuously limit wind machine speed to its specified maximum value, the well-designed wind machine always has an additional means of aerodynamic control to prevent a utility failure from allowing the wind turbine to accelerate out of control. Although it is at the cost of appreciable mechanical complication of the rotor hub, the most common and effective aerodynamic control is that of continuous control of pitch angle of the wind machine rotor blades.

Even though there is only one best angle for a particular wind machine to operate at as can be seen from the surface in Fig. 11-7, the figure also shows that increasing blade pitch can rapidly reduce power coefficient and therefore output power from the rotor. In fact, at 90° pitch the rotor should, in principle, come to rest. In real applications, especially in larger machines, there is the practical problem of pitching speed and whether blades can be pitched quickly enough to achieve the appropriate power or mechanical load reduction.

Design and testing of control algorithms that minimize fatigue damage of a wind turbine drive train and blades without lessening energy capture continues to be an important area of research.

11.5.9 Computer Simulation

Having reviewed energy collection, electrical generation, and dynamic control of wind turbines, it is not surprising that there are in general three families of computer simulation programs that provide insight into some of these areas.

There are the performance programs that simulate energy capture for hybrid electric systems. A *hybrid system* in an energy production system that combines two or more energy sources such as wind, solar, and diesel. Using either typical time history wind samples or a wind probability density curve together with a typical electrical load history, these programs will forecast the energy from the wind turbines together with the run time of any associated engine generator set. Time periods of interest are not less than months.

The next class of simulation is focused on aerodynamics, mechanical dynamics, and structures. Solutions yielded include such things as static and varying loads on structures, predicted power curves, normal vibration modes of machine components, and control system responses. Time scales treated are from seconds to minutes.

The last category includes the electrical simulations of the transients in generators and power electronics. Simulation results can warn of possible self-excitation of induction generators, overvoltages due to harmonic resonances from power electronic modules, or excess starting transient currents. Time scales used could be from microseconds to a few seconds.

Figure 11.10 illustrates three types of investigations that require different time scales. Electrical short circuits and resulting transients occur in a few seconds, while voltage regulation occurs over minutes and load following over hours.

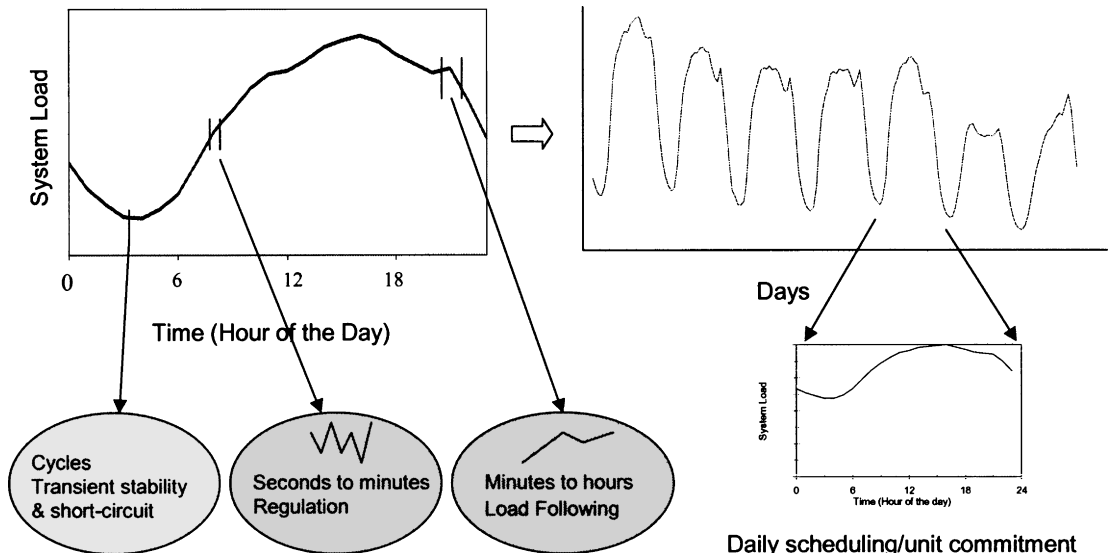


FIGURE 11-10 Three Simulation Regimes.

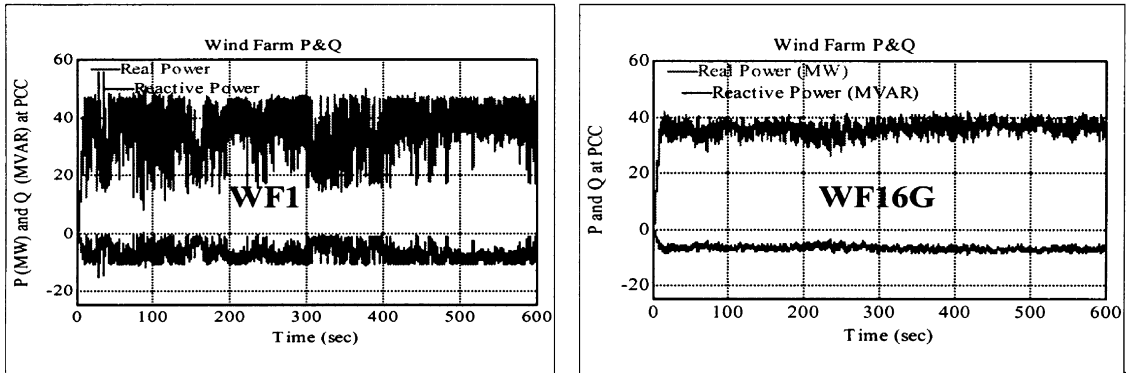


FIGURE 11-11 Real and reactive power output of a wind power plant with different aggregations.

Wind power plant designers have rightfully designed turbine controllers and safety features to disconnect and stop a turbine if it detects a fault such as a short circuit in the connection to the utility. Unfortunately, in practice, when this occurs at a wind farm of up to 50 turbines, they usually will all shut down even if the fault clears instantaneously. Each turbine must then be individually restarted. This interesting problem is called *low voltage ride through* (LVRT), and is used to describe the wind turbine's ability to stay connected during such a disturbance. The solution to this situation must be a balance between safety and inconvenience.

Figure 11-11 is an example of simulation that shows the effect of spatial diversity in a wind plant and how it naturally smoothes the power delivered.

Figure 11-11 shows a simulation of the real and reactive power of a wind farm of 200 turbines with a total rated output of 45 MW. This figure compares two methods of aggregation. The left graph shows the output of the simulation when we assume that the entire wind farm is represented by identical wind turbines, all turbines are located at the same spot and each one of them is driven by the same wind speed. Thus, the collective output of individual turbine is reflected as the output of the entire wind farm at the point of interconnection. In the right graph, the wind farm simulation groups the wind turbines into 16 different groups to simulate the diversity of a wind farm. Each group has a different number of wind turbines and is driven by a time series wind speed. Each series is time shifted with respect to other wind speed files driving different groups of wind turbines. The time shift approximates the time delay of the wind reaching different groups of wind turbines caused by differences in geographical location among the groups. Although this method is not perfect, it is closer to the reality of a wind farm. It clearly shows that the power fluctuations at the point of interconnection are significantly reduced when we consider the aggregation for 16 groups of turbines because of cancellation of the power fluctuations among the groups.

11.5.10 Issues Related to Wind Turbine Use

By Charles Butterfield, Michael Millian, Eduard Muljadi

Classes of Usage for Modern Wind Turbines. Commercially available wind turbines for electric power range in size from less than 100 W to a several megawatts. Although today wind turbines are employed in many ways, a few important classes of applications can be identified. The most publicized and largest in terms of aggregate power is, of course, the wind power plant application. Modern wind power plants can be as large as 300 MW and are often located within a short distance of each other. These wind power plants feed the same utility line. Although there are some significant policy drivers that have influenced the development of wind power plants, today wind is often economically competitive with conventional generation. It is therefore likely that significant new wind generating capacity will be developed in the next several years.

Another class called "wind-hybrid" denotes one or more midsized turbines operating in conjunction with other power sources such as a diesel generator, a photovoltaic system, and other

sources of power that are all managed by a common control system. Wind-hybrid systems provide a means to reduce the costs of electric power in outlying regions where conventional fuel is expensive and difficult to transport. Remote villages in developing countries and polar regions are the usual applications of this class.

Small turbines comprise the third class of wind turbine. They usually are privately owned for use on ranches, farms, vacation cabins, and remote communication repeater stations.

The remainder of this section is a collection of several unrelated topics that nevertheless affect the employment and acceptance of wind energy.

Certification. As in many other areas of technology, prospective buyers need to have confidence in the claims of a manufacturer. This leads to the concept of certification such as those that exists in the field of electrical appliances. The United States is participating in the development of International Electrotechnical Commission (IEC) standards for wind turbines through the American Wind Energy Association (AWEA) and the American National Standards Institute (ANSI) memberships in IEC. The IEC 61400-XX series covers design requirements, testing requirements, and certification guidelines. At present there are two dominant international certification bodies active in the European wind turbine industry: Germanischer Lloyd⁷ and Det Norske Veritas (DNV). Each certification body has developed its own rules and requirements for type certification, but they generally have the same goal: to review the design documentation and ensure that the turbine has been designed with engineering discipline in accordance with recognized industry standards, and that it will function reliably throughout its specified life. Most turbines installed in Europe must be certified by one of these bodies as a national requirement. Although the United States does not require such certifications, yet to alleviate financial risks, most commercial-scale turbines are certified.

These international certifications do not satisfy utility interconnection requirements in the United States. Interconnection requirements are usually set by individual utilities for large-scale turbines. However, the Federal Energy Regulatory Commission (FERC) is attempting to set general interconnection rules such as FERC Order 661, Interconnection of Wind Turbines. For small turbines, IEEE 1547 defines interconnection requirements that can be certified by Underwriters Laboratories (UL) and other certification bodies and are usually accepted by local electrical inspectors.

Over the past 5 years, the European community has encouraged harmonization of the different certification rules to facilitate trade within Europe. This has resulted in active standards development programs on the international level, primarily IEC.

The Wind Turbine Research Program conducted for DOE by NREL employs a comprehensive engineering development process that includes regular design, testing, and documentation reviews throughout the process. This process follows accepted international procedures, including the International Standards Organization—ISO 9001.

Grid Integration and Operational Impacts. Wind power plants have an impact on power system operations. Generally, these impacts can be divided into timescales that correspond to utility operational practice (see Fig. 10). The regulation timescale is from a few seconds to several minutes. In the regulation, timescale generation responds to small, fast fluctuations in the load, primarily via automatic generation control (AGC) computers. These fast fluctuations are generally uncorrelated.

The next load following timescale spans several minutes to several hours. Load fluctuations in this timescale are managed by generating units that are economically dispatched. Changes in load over this timescale are more highly correlated than in the regulation timescale and fluctuate over a wider range. *Unit commitment* is the process of determining which of the slow-start (thermal) units will be needed for the day-ahead schedule and ensuring those units are available when needed. Wind power plants generally increase the need for regulation and load following service and can complicate the unit commitment process. Over the planning horizon, considerations of system adequacy can be evaluated using reliability models. System adequacy is often measured by loss of load probability or a related metric. The contribution of wind power plants to system adequacy is often measured as the effective load carrying capability (ELCC) of the wind power plant. Because of the intermittent nature of the wind, ELCC as a percent of rated capacity is generally low and often falls in the range of 10% to 40% of rated capacity. Several power pools, regional transmission organizations, and other entities have developed simple approaches to calculating wind capacity value. These are detailed in Ref. 8.

TABLE 11-4 Some Samples of Integration Costs to Utilities of Wind Power Plants

Study	Relative Wind Penetration (%)	Regulation (\$/MWh)	Load Following (\$/MWh)	Unit Commitment (\$/MWh)	Total (\$/MWh)
UWIG/Xcel	3.5	0	0.41	1.44	1.85
PacifiCorp	20	N/A	1.64	3.00	4.64
BPA/Hirst	7	0.19	0.28	1.00–1.80	1.47–2.27
PJM/Hirst	0.06–0.12	0.05–0.30	0.70–2.80	N/A	0.75–3.10
We Energies I	4	1.12	0.09	0.69	1.90
We Energies II	29	1.02	0.15	1.75	2.92
Great River Energy I	4.3				3.19
Great River Energy II	16.6				4.53
CA RPS Phase I	5	0.17	0	N/A	0.17
MN DOC/Xcel	15	0.23	0	4.37	4.60

Several detailed studies have been performed to analyze the impact of wind power on system operations. The Utility Wind Interest Group (UWIG) is an organization that serves as a clearinghouse for challenges and solutions related to wind energy, and UWIG was the sponsor of one of the early studies. The general approach of the recent wind integration studies is to perform a full system analysis using standard software tools, recognizing that wind contributes an additional source of variability into an already variable system. Because the system needs to be balanced in aggregate, it is not necessary to balance each movement in wind one-for-one by a counter move of a conventional generator, and the standard simulation tools perform a system optimization that observes the requirements for balancing loads and resources. One summary of studies performed in the United States appears in Ref. 7. To analyze the impact that wind has in the regulation timescale, a method developed at the Oak Ridge National Laboratory is often used⁹. This approach allocates the regulation burden to variable loads and resources, and has been applied to wind in several analyses. Table 11-4 has been updated to reflect PacifiCorp's 2004 Integrated Resource Plan¹⁰. The table shows the range of integration costs from recent studies of wind's impact on power system operation and economics.

11.5.11 System Operation with Wind Power

By Yih-Huel Wan

When a wind power plant is connected to the grid, power and voltage fluctuations are concerns for system operators. Modern wind turbines can provide very good voltage regulations, but the power from the wind power plant is not controlled by its operators. However, actual wind power plant output data show that although wind power fluctuations are stochastic in nature, they are not completely random. Because of wind speed persistency, the magnitudes and rates of power level changes from wind power plants are seldom extreme. Wind speed does not change instantaneously, nor does power from wind power plants.

Short-time step changes of wind power are small. For example, the average magnitude (absolute value) of second-to-second step changes is less than 0.2% of the nameplate capacity for small wind power plants (with tens of turbines) and 0.1% for large wind power plants (with hundreds of wind turbines). The average magnitude of minute-to-minute step changes ranges from about 1.2% of the nameplate capacity for small wind power plants to about 0.3% of the capacity for large wind power plants. Power from large wind power plants is less variable than power from small wind power plants because of spatial variation of wind speeds. Physical separations and differences of local terrains cause wind speeds to vary. Even adjacent wind turbines within the same wind power plant do not experience the same wind conditions during short time frames and their instantaneous outputs are not likely to be synchronized (e.g., outputs from some turbines are increasing while others are decreasing). Such spatial variation in wind speeds makes the combined outputs from more turbines less volatile, especially in short time frames.

Wind power can experience bigger changes during longer periods, but average magnitudes of wind power changes for longer time steps are still relatively small. Average magnitudes of 10-min step changes range from 3% of the nameplate capacity for small wind power plants to 2% of the nameplate capacity for large wind power plants, while average magnitude of hourly step changes ranges from 7% to about 5% of the nameplate capacity.

In addition to small average magnitude of wind power step changes, the standard deviation values of wind power step changes are also small. This indicates that most of the wind power step changes are of small values and large step changes are relatively rare. As an example, Fig. 11-12 shows the distribution of 10-min wind power step changes for 1 year from a large wind power plant with a nameplate generating capacity of 100 MW. Over 98% of all 10-min step changes are within $\pm 3\sigma$ (or ± 11 MW or $\pm 11\%$ of the power plant's nameplate capacity in this case). Large swings of wind power do occur, but those infrequent large changes are almost always related to well-defined weather events such as storms and weather fronts. Most of these weather events can be accurately predicted in advance to allow system operators time to take remedial actions.

Step change statistics define the outer boundary of the wind power fluctuations. The rate of change of wind power levels in a given time interval (e.g., 10 min or 1 h) is another indicator of wind power plant behavior. Power levels from a wind power plant fluctuate continuously because the wind speed changes continuously as it moves through the wind power plant. For example, in a 1-s wind power data series, the average duration for wind power increases or decreases is only 2.2 s (with a standard deviation of 4.4 s). With 1-min data series, the average duration of the increases and decreases is 2.4 min (with a standard deviation 8.4 min). Consequently, wind power plant ramping rates are also very modest. Table 11-5 lists the wind power 10-min ramping statistics.

As shown in the table, average ramping rates are less than 0.5% of the power plant's nameplate capacity per minute. The maximum ramping rates can be large, especially for the negative ramping (rapid wind power decreases). However, such big changes occur infrequently. The distribution of ramping rates of three wind power plants for 1 year is shown in Table 11-6. It shows that wind power plant ramping rates seldom exceed 5% of the nameplate capacity per minute.

Further examination of the data indicates that not all of those very large ramping rates are the result of wind speed changes. Again, most of these large ramping rates are related to well-defined weather events that can be forecasted.

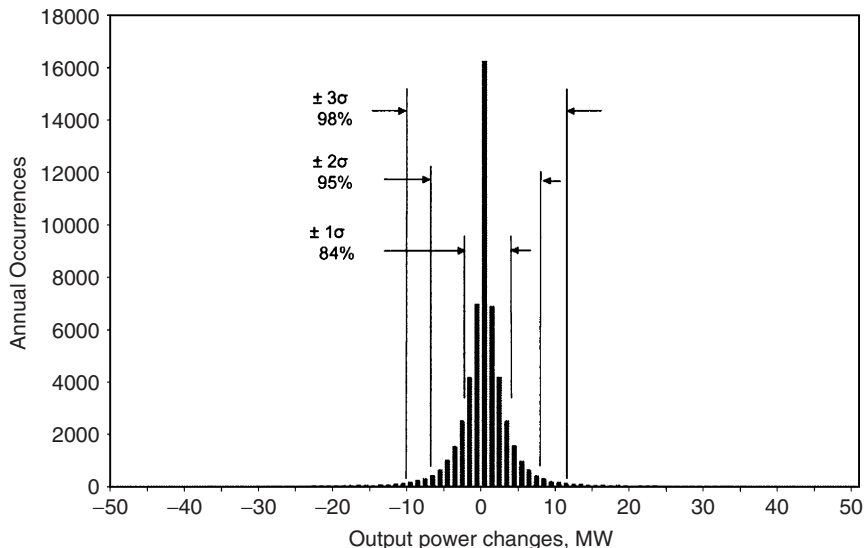


FIGURE 11-12 Wind plant power output changer during 10-min interval.

TABLE 11.5 Wind Power 10-min Ramping Characteristics

	Average		Standard deviation		Max (+)	Max(-)
	(kW/min)	(%/min)	(kW/min)	(%/min)	(MW/min)	(MW/min)
10 MW Plant	47	0.45%	78	0.74%	1.2	-1.4
100 MW Plant	269	0.26%	465	0.45%	7.0	-12.2
220 MW Plant	438	0.18%	811	0.34%	11.3	-29.0

Actual operations experience suggests that most control areas will have few problems integrating wind power at relatively low penetration levels. Utilities in several Midwestern and western states have had wind power supplying from 6% to 14% of their online loads during high wind periods. Recent studies also concluded that impacts of wind power on system operations are minor.

11.5.12 Wind Turbine Acoustic Noise

The importance of sounds emanating from a wind turbine obviously depends on its surroundings. In remote locations of the deserts of California or Texas or in offshore installations worldwide, the relatively low-level sound emitted by a group of wind machines is unimportant. In northwestern Europe, where a single machine may stand near a cluster of houses, even low-level sounds, especially at night, can be annoying. Wind turbine noise can be divided into two classes: mechanical and aerodynamic. Mechanical noise includes transmission gear tones and generator whine. These are common machinery problems and can be ameliorated by the usual methods of gear selection and soundproof insulation.

Aerodynamic noise, in turn, can be divided into impulsive and broadband noise. Impulsive noise essentially always comes from a downwind rotor blade passing behind its tower; it is caused by the sudden change in wind flow across the rotor blade. This can be modified by spiral strakes and other shapes attached to the tubular tower or changing the blade-to-tower distance. For lattice towers, the effect is somewhat less but is still present. VAWTs also have a shadow due to the central supporting column, but it is somewhat less pronounced than for HAWTs.

Broadband noise is the swishing noise of the air interacting with the turbine blades and is generated in varying degrees by all turbines. There are obviously many sources for this sound, but three important ones are blade tip vortex, blunt trailing edge airfoil, and turbulence in the wind itself. At the present writing, designers agree that broadband noise decreases with decreasing linear tip speed.

For more information on wind turbine acoustics, refer to Ref. 11.

11.5.13. Wildlife Considerations

By karin Sinclair

As wind turbines are installed across the country, concerns over possible wildlife impacts have expanded. Throughout the 1990s, the principal concern was for avian impacts. In 1992, primarily because of possible negative impacts caused by wind power development on golden eagles (*Aquila chrysaetos*) in the Altamont Pass Wind Resource Area in California, DOE and NREL, working

TABLE 11-6 Distribution of Ramping Rates

	< $\pm 1\sigma$ (78 kW/min)	< $\pm 2\sigma$ (156 kW/min)	< $\pm 3\sigma$ (234 kW/min)	< $\pm 4\sigma$ (312 kW/min)	< $\pm 5\sigma$ (390 kW/min)	> 5%/min (525 kW/min)
10 MW Plant	0.82476 < $\pm 1\sigma$ (0.5 MW/min)	0.95146 < $\pm 2\sigma$ (1.0 MW/min)	0.98305 < $\pm 3\sigma$ (1.5 MW/min)	0.99299 < $\pm 4\sigma$ (2.0 MW/min)	0.99673 < $\pm 5\sigma$ (2.5 MW/min)	0.00122 (64) > 5%/min (5.2 MW/min)
100 MW Plant	0.84047 < $\pm 1\sigma$ (0.8 MW/min)	0.95742 < $\pm 2\sigma$ (1.6 MW/min)	0.98450 < $\pm 3\sigma$ (2.4 MW/min)	0.99304 < $\pm 4\sigma$ (3.2 MW/min)	0.99619 < $\pm 5\sigma$ (4.0 MW/min)	0.00040 (21) > 5%/min (12.1 MW/min)
220 MW Plant	0.86471	0.96779	0.98856	0.99438	0.99649	0.00044 (23)

collaboratively with stakeholders including utilities, environmental groups, consumer advocates, utility regulators, government officials, the wind industry, and the National Wind Coordinating Committee's (NWCC) Avian Subcommittee, formed an active avian-wind power research program.

Avian concerns fall within two main areas: the effect of avian mortality on bird populations, and possible litigation over the killing of even one bird if it is protected by the U.S. Migratory Bird Treaty Act or the U.S. Endangered Species Act or both. After a decade of research, focused predominantly on developing solutions to reduce or avoid avian mortality caused by wind energy development throughout the United States, the DOE/NREL research task came to an end. A list of the reports generated from these research projects can be found at http://www.nrel.gov/wind/avian_reports.html.

In 1999, the Avian Subcommittee of the NWCC published guidelines for conducting avian research (Studying Wind Energy/Bird Interactions: A Guidance Document). These guidelines contain metrics and methods that should be applied to all current avian research projects. It was anticipated that the use of a standardized set of metrics and methods would help facilitate comparability among research sites.

Since DOE/NREL ended its research on issues related to avian impacts, concerns for other wildlife issues have emerged. For example, impacts on bats have become a concern as a result of high bat fatalities found at two newer wind power plants in the northeast (the Mountaineer Wind Energy Center in Tucker County, West Virginia, and the Meyersdale Wind Energy Center in Somerset County, Pennsylvania). In 2003, bat carcasses were found while conducting traditional post-construction avian fatality surveys. Although bat carcasses have been found at other wind power plants across the country, the number of fatalities found at these two sites far exceeds anything found to date. Bat-specific fatality searches have now begun at other U.S. wind power plants.

Two other issues, potential impacts on nocturnal species and grassland/shrub steppe species, have been identified by the NWCC's Wildlife Workgroup (previously known as the Avian Subcommittee). To begin addressing these issues, the Wildlife Workgroup will develop a companion document to the Guidance document, focusing on nocturnal issues such as nocturnal behavior of birds and bats. A literature review of wind power impacts on grassland/shrub steppe habitats will also be produced.

11.5.14 Summary

Over the past 30 years, wind energy has passed through its infancy and childhood and is now achieving a measure of maturity as is evidenced by the turning of researcher efforts from physics and performance of wind turbines to how energy derived from wind can better interface with today's technology and be accepted for what it can contribute. For example, the committee on wind energy within the International Energy Association now supports special groups studying *integration of wind and hydropower*, *wind energy in cold climates*, and *dynamic models of wind power plants for power system studies*.

By January 2006, the world had an installed capacity of 56 GW, and growth is expected to continue at 28% per year for a few years. In some countries, wind energy is supplying up to 20% of that nation's electrical power.

According to the IEA Annual Report, traditional technologies average electrical generation costs are in the range \$25 to \$45 per megawatthour. Levelized wind generation ranges from \$35 to \$95 per megawatthour.

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Federal Wind Energy Program

U.S. Department of Energy Wind Energy Program, <http://www.eere.energy.gov/windandhydro/>.

National Renewable Energy Laboratory, National Wind Technology Center, <http://www.nrel.gov/wind/>.

Sandia National Laboratories, P.O. Box 5800, Mail Stop 0708, Albuquerque, NM 87185-0708, http://www.sandia.gov/Renewable_Energy/.

Wind Energy Organizations

The American Wind Energy Association (AWEA), 1101-14th St, NW, 12th Floor, Washington, DC 20005, (202) 383-2500, <http://www.awea.org>

Utility Wind Interest Group, <http://www.uwig.org>

National Wind Coordinating Committee, <http://www.nationalwind.org>

Conferences

Two major wind energy conferences are held every year: Windpower and the Wind Energy Symposium. Windpower is sponsored by AWEA; the Wind Energy Symposium is held in conjunction with the AIAA Aerospace Sciences Meeting & Exhibit. Both conferences publish proceedings.

11.6 GEOTHERMAL POWER

BY RAYMOND FORTUNA

The outer crust of the earth contains a very large reservoir of energy present as sensible heat. This resource is between one and two orders of magnitude larger than the recoverable energy from uranium and thorium in the same volume of rocks. If 1% of the thermal energy contained within the uppermost 10 km of the earth could be tapped, the amount of heat would be 500 times that contained in all oil and gas resources of the world. The only natural fuel system that represents a larger energy resource on the earth is the fusion energy of deuterium.

11.6.1 Origin and Types of Geothermal Energy

Large quantities of heat that are economically extractable tend to be concentrated in places where hot or even molten rock (*magma*) exists at relatively shallow depths in the earth's outermost layer (the crust). Such hot zones generally are near the boundaries of the dozen or so slabs of rigid rock (called *plates*) that form the earth's lithosphere, which is composed of the earth's crust and the uppermost, solid part of the underlying denser, hotter layer (the *mantle*).

According to the theory of plate tectonics, these large, rigid lithospheric plates move relative to one another, at average rates of several centimeters per year, above hotter, mobile mantle material (the asthenosphere). High heat flow also is associated with the earth's hot spots, whose origins are somehow related to the narrowly focused upward flow of extremely hot mantle material from very deep within the earth. Hot spots can occur at plate boundaries (e.g., in Iceland) or in plate interiors thousands of kilometers from the nearest boundary (e.g., the Hawaiian hot spot in the middle of the Pacific plate). Regions of stretched and fault-broken rocks (rift valleys) within plates, like those in

East Africa and along the Rio Grande River in Colorado and New Mexico, also are favorable target areas for high concentrations of the earth's heat at relatively shallow depths.

Zones of high heat flow near plate boundaries are also where most volcanic eruptions and earthquakes occur. The magma that feeds volcanoes originates in the mantle, and considerable heat accompanies the rising magma as it intrudes into volcanoes. Much of this intruding magma remains in the crust, beneath volcanoes, and constitutes an intense, high-temperature geothermal heat source for periods of thousands to millions of years, depending on the depth, volume, and frequency of intrusion. In addition, frequent earthquakes, produced as the tectonic plates grind against each other, fracture rocks, thus allowing water to circulate at depth and to transport heat toward the earth's surface through these fractures. Together the rise of magma from the mantle and the circulation of hot water (hydrothermal convection) maintain the high heat flow that is prevalent along plate boundaries. Accordingly, the plate-boundary zones and hot-spot regions are prime target areas for the discovery and development of high-temperature hydrothermal-convection systems capable of producing steam that can drive turbines to generate electricity (Duffield and Sass 2003).

Water circulates freely through hydrothermal resources. For magma and hot, dry rock resources, much less water is present. The magma resource is at the highest temperature and is relatively water poor. Magmas range in temperature from about 650 to 1300°C, depending on chemical composition. The hot, dry rock resource is characterized by hot, solid rock that contains little or no water because it has few pore spaces or fractures to store and transmit water. The geopressured-geothermal resource consists of hot water saturated with methane and trapped typically in sandstones in young sedimentary basins. In the United States, this resource is abundant along the Gulf Coast in Texas and Louisiana. At present, only hydrothermal resources are used to generate electricity commercially.

11.6.2 Utilization of Geothermal Energy

Geothermal energy has been used for electricity production since 1904 in Italy, and since that time, there has been a steady expansion of this resource on a worldwide basis, with 8000 MW of installed capacity in 2004. High-grade geothermal resources are cost-effective, and in light of their environmentally benign character, the worldwide expansion is expected to continue.

Geothermal energy is immune to daily and seasonal fluctuations and therefore is a reliable power source with a high plant capacity factor. California obtained 5% of its electricity from geothermal plants in 2005. U.S. geothermal plants produce 15 to 16 billion kWh of electricity annually at costs of 4.0 to 8.0 cents per kilowatthour, which is competitive with other energy sources. Seventy plants, totaling 2600 MW of installed capacity, produce electricity in Nevada, Utah, Hawaii, and California. The first resource to be developed in the United States was the steam field at The Geysers, about 90 miles north of San Francisco. The Geysers steam field has produced electricity since 1960 and is the largest geothermal power plant development in the world.

Commercial production of electricity from geothermal resources has been carried out for 40 years in New Zealand and for over 30 years in Japan. Power production is currently under way in Australia, China, Costa Rica, El Salvador, Ethiopia, France (Guadeloupe), Guatemala, Iceland, Indonesia, Italy, Japan, Kenya, Mexico, New Zealand, Nicaragua, Philippines, Portugal (Azores), Romania, Russia, Thailand, and Turkey.

For steam-dominated resources, naturally occurring dry steam can be used directly in a fairly standard, low-pressure steam turbine to generate electricity. The steam is produced via geothermal wells and fed to the turbine through insulated pipes. Power plant developments at The Geysers, California, and Larderello, Italy, use dry steam.

Liquid-dominated geothermal resources are more common than steam-dominated resources. If resource temperatures are sufficiently high ($>171^{\circ}\text{C}$), the liquid can be flashed partially to steam for use in a steam turbine using a single-flash or double-flash process. If the geothermal reservoir fluid is in a compressed liquid state, it partially flashes to steam in the wellbore as it rises to the surface. Additional steam is separated in surface flash tanks and fed to the turbine. The remaining liquid is injected back into the reservoir. If the resource temperature is high enough, the fluid can be flashed twice. Flashing occurs in the well and in a first separator at the surface. The high-pressure steam is fed to the high-pressure stages of the turbine. The liquid fraction from the first separator is flashed

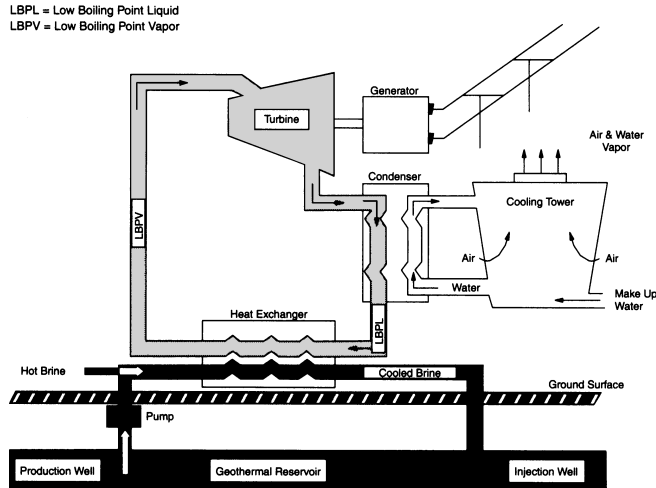


FIGURE 11-13 Schematic diagram of a binary geothermal power plant. (U.S. Department of Energy)

again in a second, low-pressure separator. The additional steam is fed to the low-pressure stages of the turbine. The addition of a second flash increases plant efficiency by about 20% compared with single-flash systems.

For liquid-dominated geothermal resources at resource temperatures not sufficiently high enough for flash systems, a binary cycle (organic Rankine cycle) is used (Fig. 11-13). The geothermal fluid is used to heat a working fluid with a low boiling point, such as refrigerants, isobutane, or propane. The heat of the geothermal brine is transferred to the pressurized working fluid in heat exchangers. The working fluid is vaporized and expanded through a turbine to produce power and then condensed and recycled through the heat exchangers in a closed cycle. The cooled brine is injected into the reservoir. Flash and binary cycles are combined sometimes to maximize the efficiency of extracting energy from a single stream of geothermal fluids. Typically, the binary cycle operates in a “bottoming” mode, using the outflow from a flash plant as its input.

In sizing large geothermal power plants, it is important to note that (1) the cost of fluid collection and injection increases as more wells are required, and (2) the relative cost of piping and the amount of heat lost in fluid transmission both increase as the distance between the resource wells and the plant increases. With increased system size, beneficial economies of scale of larger turbine-generators are traded off against the increased cost of the brine-gathering system. Geothermal power costs are sensitive to wellhead temperatures, well flow rates, and well costs. These three parameters determine to a large extent the economic value of a geothermal resource. The thermodynamic efficiency of the conversion process increases with higher resource temperatures. The size and cost of many power plant components vary inversely with temperature and directly with total fluid flow through the plant. Power plant costs increase as resource temperatures decrease because thermodynamic efficiency declines, and the heat content of the geothermal fluid is also less, requiring more mass per kilowatt. At some reservoirs, however, shallow, low-temperature wells can be inexpensive and very productive. Therefore, in some cases, low-temperature geothermal resources still may provide cost-effective power (DOE/EE-0044).

11.6.3 Exploration for Geothermal Energy

Exploration identifies geothermal resources, estimates resource potential, and establishes resource size, depth, and potential production. Refinements of exploration techniques evolved from those used in the petroleum and mining industries. Geothermal exploration of unmapped regions typically

proceeds in two basic phases: (1) reconnaissance, or delineation of one or more geothermal provinces; and (2) detailed exploration for exploitable reservoirs within the provinces.

During the first phase, reconnaissance, regional geology and fracture systems are studied, such as young volcanic features, tectonically active fault zones, and overt or subtle geothermal manifestations. To design specific exploration programs, information is collected from various sources, including regional geologic and geophysical maps, satellite imagery, geochemical sampling of thermal and nonthermal waters and gases, analysis of surface rocks and soils, aerial photography, and measurement of thermal gradients in existing wells. If the reconnaissance phase proves satisfactory, the second phase of detailed exploration focuses on individual prospects. The first step in detailed exploration is geologic mapping on scales of about 1:6000. The objective is to understand the broad distribution of rock types, alteration zones, faults, fractures, and thermal features. Geochemical studies also are undertaken, and the collected information is integrated to produce a preliminary model of the area. Geophysical surveys are used to refine the preliminary model. If the model is encouraging, thermal-gradient wells are drilled to depths of 100 to 600 m. These wells provide the first strong direct evidence of the location and intensity of thermal energy. If indications of a hot resource are strong, the first deep hole, a "wildcat well," is drilled. If the wildcat is successful, it is followed by additional production-sized wells to confirm and assess the resource (DOE/EE-0044).

11.6.4 Drilling for Geothermal Energy

Power-generation systems require deep production and injection wells to produce and dispose of the geothermal fluids. The predominant method for drilling these deep wells is rotary drilling, adapted from the oil and gas industry. There are major differences between geothermal well drilling and oil and gas well drilling. Temperatures of geothermal fluids may reach 400°C compared with 200°C for deep oil and gas basins. These high temperatures cause rapid degradation of ordinary drilling equipment and drilling fluids. Production pressures for geothermal reservoirs are usually very low, in many cases subhydrostatic. The underpressured reservoirs can become plugged if ordinary high-density drilling muds are used. To overcome this situation, compressed air, aerated fluids, or foam is used. Geothermal formation rocks are usually more abrasive and harder than petroleum formation rocks. These formations severely degrade bits and tubular materials, especially when air is used as the drilling fluid. High temperatures also cause elongation of the wellhead and casing. Tolerance for casing motions must be accommodated when designing the wellhead, and geothermal wells are cemented from top to bottom to control the effects of casing elongation.

Drilling is one of the most expensive activities in any geothermal power development project. Each well can cost \$1 to \$3 million, and an average geothermal field consists of 10 to 100 or more wells. Drilling costs account for one-third to one-half of the total cost of a geothermal project.

11.6.5 Geothermal Reservoir Engineering

Reservoir engineering involves (1) formation evaluation, (2) reservoir modeling to forecast productivity and longevity, (3) well field management, and (4) analysis of production trends. Information derived from these activities is used to formulate a production strategy that balances the cost of delivered power or fluid with reservoir longevity.

Formation Evaluation. A number of techniques are used prior to production to evaluate the properties and flow parameters of the reservoir rock, to identify major fluid-bearing fractures and permeable rocks, and to understand reservoir-well interactions. Some of these techniques are analysis of well logs, drill cuttings, and drill cores to derive reservoir parameters such as permeability, porosity, and fracture characteristics; analysis of injected tracer return patterns to define the movement of fluids in the reservoir; pressure-transient well tests to determine the controlling flow and storage capacity of the formation and to delineate reservoir boundaries and heterogeneity; laboratory analyses of reservoir rocks and fluid samples; borehole televIEWer, caliper, and spinner (flowmeter) surveys to locate fractures downhole; large-scale seismic arrays to record the pattern of seismic events in the

reservoir; magnetotelluric analysis of the reservoir structure; and experimental geophysical and geochemical techniques to locate and map fractures and other geologic features.

Reservoir Modeling. An initial conceptual model of the reservoir, used to estimate its production capacity, is generated in the early stages of production and is updated continuously. The early reservoir model is then expanded from a conceptual model to a complex two- or three-dimensional numerical model. A variety of techniques can be used, including conceptual geologic modeling to define the geometry and physical properties, numerical simulation of reservoir behavior under production and injection conditions, geochemical modeling to analyze changes in reservoir fluids and rocks and to predict the movement of chemical fronts, analysis of well test data to determine key reservoir parameters, and wellbore simulation to analyze fluid flow and heat transfer inside the wellbore.

Well Field Management. Well field management optimizes production strategies. Well field management begins with the initial production stage and continues through the entire production period. Techniques include well field design optimization considering appropriate variations in well locations and depths, production rates and methods, fluid injection locations and rates, and production and injection control strategy; cost-benefit studies of energy extraction rates versus the cost of flashing flow or pumped production; improved injection techniques and injection well replacement strategies to increase production through heat sweep from the reservoir rocks; monitoring subsurface fluid movement using high-precision gravimeters; studies of water-rock interactions, sources of corrosion, and corrosion mitigation; use of liquid-phase and vapor-phase tracers to understand fluid movement within the reservoir; and monitoring microseismic activity to understand the stress vectors in the reservoir and the distribution of productive and/or receptive fractures. Microseismic monitoring also can reduce any environmental concerns that the production or injection of fluids may cause significant seismic activity.

Determination of Reservoir Production Trends. The monitoring of long-term production histories helps to understand reservoir production trends, reservoir–power plant system performance, and reservoir longevity. Recent advances in computer technology facilitate data storage and analysis and enhance the use of reservoir simulators. Methods used are long-term monitoring through geophysical measurements and geochemical sampling to detect fluid depletion and recharge ratios, microseismic monitoring of injected fluid to trace flow patterns and associated fracturing, numerical simulation of nonisothermal flows of multicomponent, multiphase fluids in porous and fractured media, and numerical simulation of multiphase, multicomponent aqueous species and noncondensable gases to model phase partitioning of components, conductive and convective heat flow, relative permeability effects, capillary pressure, and flow in fractured media.

11.6.6 Research and Development

Geothermal research and development activities are continuing worldwide. Improvements in the following areas are expected to have significant impacts: (1) techniques to identify and locate geothermal resources, (2) improved equipment and methods for well drilling and completion, (3) improvements in reservoir engineering, modeling, and management techniques, (4) advanced materials and improved power conversion cycles, and (5) permeability enhancement methods. Exploration techniques being refined include seismic imaging, spontaneous potential, three-dimensional magnetotelluric, gravity, electrical resistance tomography, transient electromagnetic, hyperspectral and satellite imaging, fracture and strain detection, and geochemical surveys. Drilling research and development (R&D) includes high temperature electronics and batteries, polycrystalline diamond compact (PDC) bits, mudjet augmented bits, downhole fiber optics, diagnostics-while-drilling, phosphate and sodium silicate-based well cements, and lost circulation control. For reservoir management, research areas include new chemical tracers, reservoir-wellbore simulators, and injection techniques. Power plant R&D includes innovative power cycles, hybrid wet-dry cooling, noncondensable gas removal, enhanced air-cooled condensers, coatings to prevent corrosion, hydrogen sulfide abatement, and silica recovery from geothermal fluids.

Three hot, dry rock pilot projects are active: the Soultz project in France, the Bad Urach project in Germany and the Cooper Basin project in Australia. These projects involve fracturing rocks of low

permeability and conducting water circulation tests to extract heat from the human-made reservoirs. Other hot, dry rock experiments have been conducted at the Fenton Hill site in New Mexico, the Rosemanowes site in Cornwall, England, and the Fjallbacka site in western Sweden.

Techniques to increase permeability in marginally productive natural *hydrothermal* systems are being tried at sites in the western United States. These experiments are being conducted at the margins of productive geothermal fields and are referred to as *enhanced geothermal systems*.

Geothermal heat pump (also called *ground-source heat pump*) technology is making significant strides. The geothermal heat pump uses the earth as a heat source for heating or as a heat sink for cooling. A water and antifreeze mixture circulates through a pipe (usually polyethylene) buried in the ground (vertically or horizontally) and transfers thermal energy to a heat exchanger in the heat pump. The heat exchanger is a water-to-refrigerant loop. The ground-loop heat exchanger rejects heat from the condenser or delivers heat to the evaporator, depending on the mode of operation. Instead of a ground loop, groundwater can be used as the heat source and sink where groundwater is available and disposal of groundwater is acceptable. Geothermal heat pumps offer the advantage of a more stable source/sink temperature when compared with air-source heat pumps and can reduce electricity consumption by up to 30%. Researchers are reducing the cost of ground-loop installations, examining the practicality of adding supplemental heat rejection devices, and developing in situ tests and software to estimate the thermal conductivity of the soil and rock.

Low- to moderate-temperature resources ($<150^{\circ}\text{C}$) are used increasingly for space heating, aquaculture, crop drying, and industrial processes. A well brings hot water to the surface, and a system of piping and heat exchangers delivers the heat to the space or process. A disposal system either injects the cooled water underground or disposes of it on the surface. Worldwide, geothermal direct use installed capacity totals more than 12,000 MWt, with 600 MWt in the United States.

11.6.7 Economics

For 5-MW and larger power plants using high temperature resources, the capital costs for the exploration, wells, and power plant range from \$1,150 to \$2,100 per kilowatthour. For 5-MW and larger power plants using moderate temperature resources, the capital costs range from \$1,350 to \$2,500 per kilowatthour. O&M cost range from 0.4 to 0.8 cents per kilowatthour for these plants. These costs are based on World Bank data, and future costs are expected to decline based on technology improvements. DOE/EPRI document EPRI/TR-109496 summarizes additional cost data for flash and binary power plants.

Competition from low-cost electricity from natural gas has strongly affected the development of geothermal power plants in the western United States. Approximately 900 MW of geothermal power plants were installed in the western United States between 1980 and 1990. However, since about 1990, the advent of cheaper electricity from natural gas-fueled systems and low load growth rates have slowed the pace of development. In 1990, geothermal power developers expected to compete against power at 6 to 7 cents per kilowatthour in 1996. By 1993, however, the developers were competing against power at 2.5 to 3.5 cents per kilowatthour in western states. However, strong overseas markets for these systems continue to provide a strong base for ongoing technology improvements and new federal tax credit and . . . increase in the United States are expected to . . . future development.

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11.7 ENERGY STORAGE

BY MOHAN V. AWARE

Introduction

Energy is manifested in mechanical, electrical, chemical, and thermal forms—the latter being a special form of mechanical energy. Energy may be converted from any of these forms to any other form by one or more intermediate processes. Energy is stored in order to match energy supply with demand and/or to contain it for transport to a point where it can be used. Energy can be stored mechanically, electrically, chemically, or thermally. An energy-storage system generally comprises a converter to alter the energy from the type available to the type best stored, a storage subsystem which contains and stores the energy, and a reconverted subsystem to transform the stored energy to the type needed. The motivation for building and using storage is economics, since storage systems would displace generation equipment fired with premium fuels.

In this section, review of the various types of electrical energy-storage systems that store energy in a variety of forms but whose input and output are electrically presented. The review will include a brief description of the theory underlying the operation, a discussion of engineering concepts including conversion and reversion methods, and an outline of the specifications and applications for each storage system.

All energy-storage devices have a fixed quantity of usable energy. Once the energy has been consumed, the device will have to be refilled or charged. The quantity of energy or hours of storage of an energy-storage device are determined largely by its intended application and by the incremental cost for the storage subsystem. In the deregulated environment of electrical energy systems, the cost-effectiveness of these storages is having special importance. Research and development is ongoing for all areas of energy storage. Some of the primary energy storage development goals include

- Lower costs
- Longer life
- Higher efficiency

Over the years, a lot of energy storage systems for electrical energy were developed. The most frequently used systems are shown in the Fig. 11-14. When energy is produced in the form of electricity,

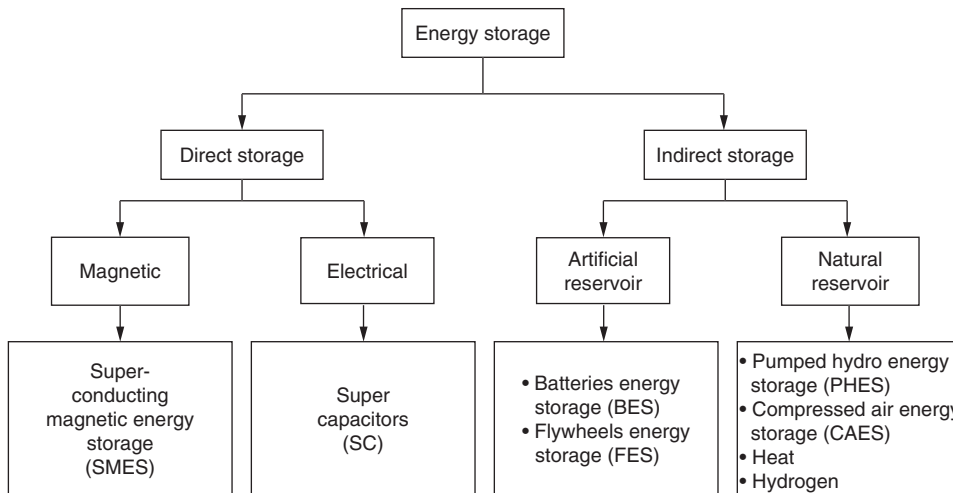


FIGURE 11-14 Energy storage system.

it has to match the load demand. There is no facility to allow the storage of electricity to facilitate the generation interdependently of the load demand. This needs intermittent energy storage devices. The application of these devices in sustainable energy systems is presented with their interface to main system in following sections.

11.7.1 Electrochemical Energy Storage

Batteries. The most traditional of all energy storage for power system is the electrochemical energy storage (EES). The major classification can be made in three categories. They are primary batteries, secondary batteries, and fuel cells. The common feature of these devices is primarily that stored chemical energy is converted into electrical energy. Although the input and output energy of a battery is electrical, the storage is in the chemical form. The most widely known device is the conventional lead-acid battery. The technology is mature and the costs are fairly well-known. The battery life is fairly long, perhaps 10 years or more when properly maintained, but the initial cost is high if one wishes to store enough energy for significant use. In some cases, however, it is the only thing available. In such circumstances, it may be used to operate few lights, television sets, and similar low-demand devices. More effective use of batteries for energy storage awaits the development of more efficient and less costly batteries.

Electrolysis of water represents another technique for storing energy in chemical form. The stored product of hydrogen can be used as fuel. To minimize storage requirements, it must be stored at relatively high pressures, and even so the energy density is fairly low. Greater energy densities could be achieved by liquefaction, but the mechanical and cryogenic technologies required are expensive. One of the major attractions of this approach is that the basic raw material is distilled water, and it is possible to develop similar devices to run on hydrogen directly. These include simple heaters and internal-combustion engines. The former could be used for space heat, grain drying, cooking, etc., and the latter could be adapted to small range vehicles such as mini-tractors and mini-trucks. In certain rural situations, these devices could be useful and would not require imported fuel.

Lead-Acid Batteries. One of the oldest and best-known devices used to store energy is the lead-acid battery. The technology is based on the reduction of lead dioxide to lead sulfate at the positive electrode and the simultaneous oxidation of the lead to lead sulfate at negative electrode. The electrolyte, sulfuric acid, is consumed and energy is discharged during this process. Energy is stored by reversing these reactions, that is, charging the battery.

The energy stored is proportional to the voltage (2.08 V per cell) and to the amount of lead. Lead has a high molecular weight, is an inherently inefficient chemical for battery energy storage, and is used for carrying current in cell. As a result, the amount of lead required per kilowatthour of storage is 50 to 100 lb, which unfavorably affects both the weight and cost of the storage system. A serious drawback of this battery is therefore its low energy density (i.e., energy stored per unit weight of battery), which is about 10 to 25 Wh/lb depending also on design and operation. Under suitable operating conditions, a well-designed and manufactured lead-acid battery can achieve 2000 cycles and last for 10 years. However, life is substantially sacrificed to achieve higher energy densities required for certain application, such as electric vehicles.

A lead-acid battery system comprises individual cells that have capacity range from a few tenths of a kilowatthour to a few kilowatthours. A large submarine cell can have a capacity of 10 kWh and weigh 1,000 lb. Lead-acid cells are often arranged in series strings to achieve the desired dc voltage for conversion or for the application intended. The number of strings will depend on the energy requirements. Energy conversion is often achieved by solid-state converter/rectifier systems. Lead-acid batteries are used in submarines, forklift trucks, uninterrupted power supplies, electric vehicles, and short-term emergency power systems for several applications including telephones, computers, and nuclear power stations. Lead-acid batteries are also being considered for electric utility application. West Berlin's utility (BEWAG) installed a 8.6 MW/9.3 MWh lead-acid battery system in 1987 to meet a part of its system regulation (maintaining frequency stability) and spinning reserve needs (supplying short-term emergency power).

Nickel-Cadmium and Other Commercial Batteries. The nickel-cadmium battery is the only other commonly employed rechargeable battery besides lead-acid. The chemical reaction involves reduction of nickel oxide to nickel hydroxide and oxidation of cadmium to cadmium hydroxide in an alkaline electrolyte (20% to 35% potassium hydroxide). The voltage of this couple (1.3 V) is less than that of lead-acid, and the energy density (about 20 Wh/lb) is slightly better. Due to the high costs for nickel and cadmium, this battery is expensive and is only used when extremely long life or lighter weight is required. Major applications are satellites, portable equipment and tools, and various military applications. Other secondary (rechargeable) batteries considered for these and their specialized application are silver-zinc, nickel-iron, and nickel-hydrogen. These systems are all expensive and are less environmentally friendly, but they are durable and have very long lives. Compared to lead-acid battery, the higher reliability of individual cell is offset by the larger number of cells required.

Advanced Batteries. Over the past two decades, a number of advanced batteries have been investigated. The aim of the research programs has been to lower the costs while maintaining the desirable specifications (durability and performance) of the lead-acid and nickel-cadmium batteries. A secondary objective is to achieve improved energy densities. The advanced battery systems closest to commercialization are zinc-chloride, zinc-bromide, and beta (sodium-sulfur) batteries. These are compared in Table 11-7. In contrast to the lead-acid and nickel-cadmium systems, these advanced batteries use low-cost, readily available active materials and enjoy simple electromechanical reactions, which should lead to excellent durability.

These advanced batteries either operate at higher temperature (Na-S) or employ flowing electrolytes (Zinc-halogen). The additional subsystems for such batteries to maintain flow or temperature add to overall system complexity, which in turn, affects their reliability. However, these subsystems normally will be built within the battery system and will have the same modular character of the lead-acid battery. As a result of these additional subsystems, optimal economics will not occur until module sizes are in the 100- to 400-kWh range, a factor of 10 larger than the largest lead-acid battery modules. The size of module will have application only where there are fairly sizable energy storage requirements, such as electric utility and commercial or industrial applications, which require a capacity of few hundred kilowatts to several megawatts. While there is hope that these advanced batteries can be used for electric-vehicle application, their economic optimal size and complexity suggest that the economic goals for this application will be difficult to achieve. An electric-vehicle battery has to be inherently simple from both the design and engineering standpoint to meet owner expectations.

The advanced batteries are not yet commercially available at affordable costs. Engineering prototypes of the zinc-chloride system at a size of 500 kWh began independent testing in early 1984. Similar-sized prototypes of the other advanced batteries were tested in 1991. Limited commercial availability of these systems can occur within a few years of successful independent testing. However, acceptable costs may occur for yet an additional 3 to 5 years, and only with a reasonable market.

Fuel Cells. A *fuel cell* is an electrochemical device wherein the chemical energy of a fuel is converted directly into electric power. The main difference between a conventional battery and a fuel cell is that, unlike a battery, a fuel cell is supplied with external reactants; as a result whereas a battery is discharged, a fuel cell never faces such a problem as long as supply of fuel is provided. Fuel cells, distinguished from other secondary batteries by their external fuel store, have an even longer history than the lead-acid battery. The first hydrogen-oxygen fuel cell was demonstrated in principle by English lawyer W. R. Grove in 1839, although the bulk of fuel cell's development has been in the

TABLE 11-7 Advanced Battery Systems

System	Positive electrode	Negative electrode	Cell voltage	Temperature, °C	Achievable energy densities, Wh/lb
Na-S	S	Na	2.1	300–350	45–55
Zn-Cl	Cl	Zn	2.1	20–50	30–40
Zn-Br	Br	Zn	1.8–1.9	20–50	20–30

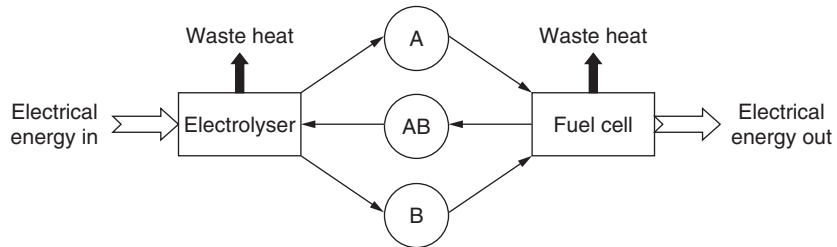


FIGURE 11-15 Schematic diagram of an electrochemical fuel cell.

last 40 years and the major application has been in the space industry. Major research activity in secondary batteries worldwide is concerned with material research for advanced batteries, in particular, materials for solid solution electrodes and for solid electrolytes. It should be noted that solid electrolytes are equally applicable to an electrochemical fuel cells. The processing functions of an electrochemical fuel cell are presented in Fig. 11-15.

Essential functions of the fuel cell are

1. The charging (or electrolyser) function in which the chemical AB is electrochemically decomposed to A and B.
2. The storage function in which A and B are held apart.
3. The discharge (or fuel cell) function in which A and B are reunited with simultaneous generation of electricity.

Fuel cells are generally characterized by the type of electrolyte that they use. Main fuel cell systems under development for practical applications are phosphoric acid (PA), proton exchange membrane (PEM), molten carbonate (MC), solid oxide (SO), direct methanol (DM), and alkaline fuel cell.

The different types of the fuel cells are having their respective properties and applications. A typical fuel cell-based power processing system showing the major plant processes is shown in the Fig. 11-16. There are three major steps involved in the generation of the power from a fuel cell. The first and foremost step is achieved purity of the available hydrogen gas. This is done with the help of a fuel processor. A carbonaceous fuel is fed to the fuel processor, which in turn, produces a hydrogen rich gas at its output. This hydrogen rich gas is then fed to the anode electrode of the fuel cell. The second step involves the fuel cell operation itself. The fuel cell is fed with the hydrogen rich gas at its anode and supply of air to the cathode. The hydrogen atoms at the anode gets split up into positive protons and negative electrons. These electrons follow an external path on their way to the cathode, thus supplying power to an external load in the process.

The third step is the power conditioning step, which includes power electronic converters. Power electronic converters add more flexibility to the operation of the system.

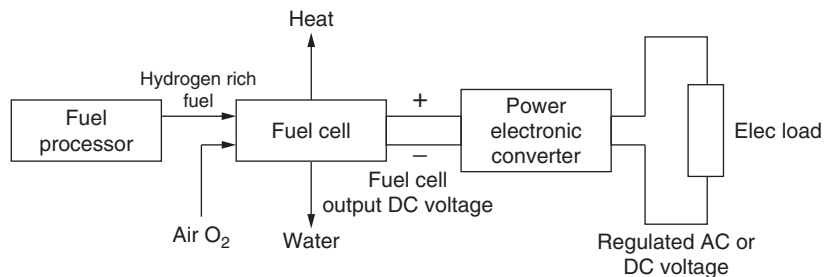


FIGURE 11-16 Typical fuel cell-based power processing system.

11.7.2 Mechanical energy storages

Flywheels. Mechanical energy may be stored in the form of kinetic or potential energy. A flywheel, in essence, is a mechanical battery—simply mass rotating about an axis. Although the use of the flywheel as a kinetic energy storage device is well-known, it has not, until recently, been considered practical to build flywheels that could store energy for several hours or days. They take an electrical input to accelerate the rotor up to speed by using the built-in motor, and return the electrical energy by using this same motor as a generator. Steel flywheels have been used to power certain types of vehicles, such as buses and trucks, for very short runs, but the energy-storage periods have at the best been for a few minutes.

The basic problems of flywheels are as follows. First, the stress in any rotating structure is proportional to the first power of the diameter and second power of the angular velocity. With steel structures, the limiting stresses are exceeded before any significant amount of usable energy can be stored. Second, even if the flywheel could store significant energy, it would soon be dissipated by bearing friction and windage losses. It has been pointed out by Post and Rabenhorst that one or two orders of magnitude improvement over conventional flywheel technology could be achieved by

- (a) Using fiberglass resins and polymer materials, which have a much higher strength-weight ratio than steel.
- (b) Running the flywheel in a vacuum.
- (c) Using air-or magnetic-suspension bearing technology developed in recent years.

If the projections of Post and Rabenhorst are supported by experimental evidence, it appears that flywheel could become practical for storing significant amount of energy efficiently for several hours. This could make flywheel practical for electrical peaking and short-run vehicular transportation.

Flywheels involve the storage of kinetic energy in a rotating object. The stored energy is proportional to the object's moment of inertia times the square of its angular velocity. In order to optimize the energy-to-mass ratio, the flywheel needs to spin at the maximum possible speed. For a flat disk, the moment of inertia is proportional to its mass times the square of its radius. Therefore, the energy stored is proportional to its mass and the square of angular velocity. Rapidly rotating objects are subject to centrifugal forces that can rip them apart. Thus, while dense material can store more energy, it is also subject to higher centrifugal force and thus fails at lower rotational speeds than low-density materials. Therefore, tensile strength is more important than the density of the material. Two approaches to flywheel energy storage are generally pursued. The commonly used approach is to use a heavy material, like steel, and operate at a moderate speed. The other approach, the so-called advanced flywheel, uses lighter high-strength materials like glass or carbon fibers and operates at high speed. Recent advances in composite materials technology may allow nearly an order of magnitude advantage in specific strength of composite when compared to even the best engineering metals. The result of this continuous research in composite has been a flywheel that operates at rotational speed in excess of 100,000 rpm with tip speeds in excess of 1000 m/s.

Flywheels have smoothed our energy sources in such historic applications as the potter's wheel, the grain mill, and the water wheel. Today, its best use is in engines of various types. For large-scale electric storage, economics would dictate the use of lighter-weight high-speed (30,000 r/min) wheels operating in a vacuum and using magnetic bearings to reduce friction. Under these conditions, energy efficiencies of about 80% are achievable. Since the speed of the wheel will change as energy is added or withdrawn, the motor-generator will have to accommodate variable speeds. Several approaches to variable-speed generation have been investigated for wind application, although today's wind machines use fixed speed generators. Conservation measures have encouraged the use of variable-speed motors, and several manufactures now have this technology available in large sizes, for such applications as thermal power plant fans and pumps. The flywheel itself is an expensive way to store energy, with costs probably twice that of the lead-acid battery. However, it has several advantages over chemical energy storage, like energy density and better capability to exchange energy.

However, for application such as utility system regulation, where there are high-power and low-energy requirements, flywheels would be suitable if integrity and reliability can be demonstrated. The ideal use for today's flywheels is still to absorb and dissipate mechanical energy to smooth the

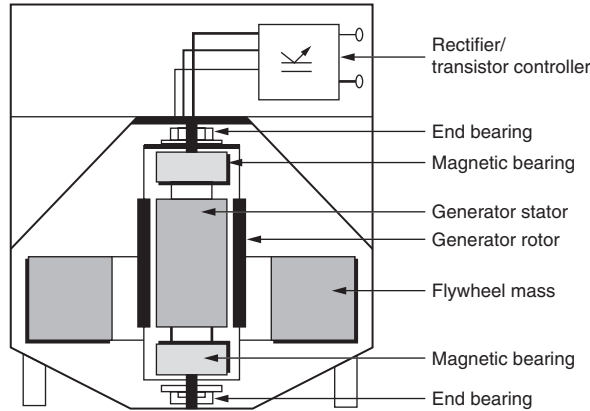


FIGURE 11-17 Flywheel storage system.

operation of rotating machinery. The ultrahigh rotational speed required to store significant kinetic energy in these systems virtually rules out the use of conventional mechanical bearings. Instead most systems run on magnetic bearings. These relatively recent innovations use magnetic forces to levitate a rotor, eliminating the frictional losses inherent in rolling element and fluid film bearing. Unfortunately, aerodynamic drag losses force most high speed flywheels to operate in a partial vacuum. A modern high-speed flywheel system is shown in Fig. 11-17.

Pumped Storages. Mechanical energy may be stored in the form of potential energy by pumping water to a reservoir at a higher level and allowing it to flow down to a lower reservoir whenever the energy is required. In this pump-back system, the kinetic energy of the flowing water is usually converted to electrical energy, although it can be used directly as mechanical energy. The energy can be extracted from the hydro power plant depending on both the volume of the water available and the head of the water that can be exploited. The pump storage will provide the most efficient and cheapest operation when it can be provided a high head between the two reservoirs. This will allow greatest amount of energy to be stored in the smallest volume of water resulting in a smaller pump and turbine, reducing capital costs. Pumped hydro storage usually comprises the upper reservoir, waterways, a pump, a turbine, a motor, a generator, and lower reservoir as shown schematically in the Fig. 11-18.

A difficulty of the pump-back storage system is that relatively large reservoirs are required. Most pump-back systems are built where there is a large natural basin for an upper reservoir located near an existing lake or river, the latter serving as the lower reservoir. With current technology in pump-back systems, generally about two-thirds of the energy is available for utilization after storage.

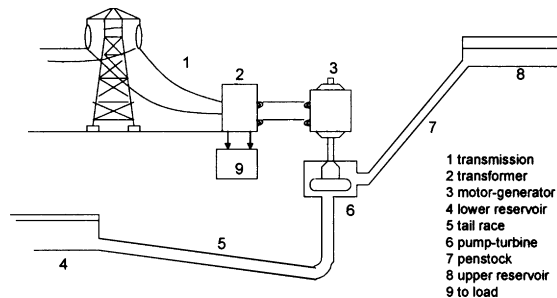


FIGURE 11-18 Pumped hydroelectric energy storage.

Hydraulic turbines have a maximum efficiency of around 95% and pumps are less efficient operating around 90%. Therefore, pump storage plants will have maximum efficiency of around 85%.

Pumped hydro or pumped storage, as it is often called, has been used in electric utility systems for over 50 years. Electricity is used to operate a motor-generator combination to pump water to an elevated reservoir. When energy is required, water is allowed to flow down to a lower reservoir through a turbine-generator combination, much like the turbine generators in conventional hydro-electric plants. The energy stored is proportional to the head (height differential between the upper and lower reservoir) times the stored volume of water. For head of 1200 ft, 36 ft of water is required for generation of 1 kWh. For a head of 120 ft, 360 ft of water is required to generate 1 kWh.

In areas where topographic or ecological considerations rule out pumped-hydro plants, utilities now may choose to go underground. A modification of pumped hydro, underground pumped hydro (UPH) would have its lower reservoir located about a mile below the earth's surface in a competent hard-rock cavern. A UPH plant therefore can be sited in flat terrain and should have only a minimal effect on the surrounding environment. The most significant drawback of UPH is that the plants must be in huge sizes (2,000 MW/20,000 kWh) to be economically attractive.

Both pumped hydro and UPH, like conventional hydro, have very fast response characteristics (emergency full-power capability is 10 s) and very high efficiencies (72% to 75%). These factors, along with low capital costs, have led to the construction and operation of 18,000 MW of pumped hydro in the United States. Another 16,000 MW is planned or under construction. Pumped hydro typically will be the storage alternative of choice for electric utilities having favorable topography. Main barriers for the future growth in pumped-hydro capacity are the availability of suitable sites and large environmental impact of these schemes.

Compressed Air. Another method for storing mechanical energy is through compressed air. Two basic methods are of interest: direct compression and isothermal compression. Direct compression, to be practical, requires the availability of natural or man-made underground caverns, which can be sealed off and pressurized to hydrostatic pressure or below. Utilization of the stored energy requires the availability of low-pressure turbines or piston engines similar to the old-style steam engines. Generally, such systems provide a relatively low overall efficiency. About one-third of initial energy can finally be utilized. This figure can be improved considerably when compressed-air system is combined with gas turbine cycles or with refrigeration cycles, because the energy required to compress the turbine inlet air need not be charged against turbine fuel efficiency if the air is already compressed.

Of increasing interest is isothermal hydraulic compression. In this process (which is at least 3,000 years old), a vertical tube is placed in front of a dam which is creating a head of water (typically 5 to 10 m). Water flowing into the inlet entraps air bubbles, which are carried with water. The water then passes through the bottom of a sealed tank or cavern, where the air bubbles rise. Ultimately, the air in the tank or cavern is compressed to a pressure slightly under the hydraulic head of the vertical (venturi) tube. That compressed air can then be used in a simple turbine or other suitable expander to obtain usable mechanical energy. Such isothermal hydraulic compressors were used from ancient times until the later part of the nineteenth century, when they were gradually replaced by electrical, steam, or internal-combustion devices. Because the compression is isothermal, the apparent efficiency of such systems can be very high, and with the rising cost of fuel, interest in this storage system is rapidly rising. A typical air-storage gas-turbine power plant with a constant pressure reservoir is shown in Fig. 11-19.

CAES involves the compression of air into an underground cavern or reservoir (excavated rock, solution-mined salt, or aquifer) where it is stored. Favorable geologies exist in about 75% of the United States. Geologic considerations generally dedicate that most of the heat of compression be removed (and used or stored, if possible) before the air is stored underground. During generation, the air is expanded through a turbine to drive a generator. Economics dictates that heat be added to the air from a thermal store or through combustion of fuel prior to the expansion-generation phase.

CAES technology recently has become commercialized for electric utility application. The commercial units incorporate modified combustion turbines wherein the compressor and expander are physically separated by clutches and motor-generator. For the expansion-generation phase, the technology uses oils or gas, although other fuels can be used. When a heat exchanger is incorporated to use exhaust heat to raise the temperature of the pressurized air, the overall energy balance involves approximately

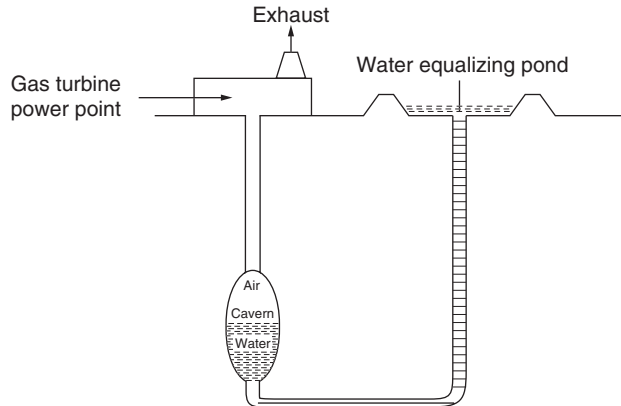


FIGURE 11-19 Air-storage gas-turbine power plant with a constant pressure reservoir.

4,000 Btu of oil or gas (during the generation phase) and 0.775 kWh of electricity (for the compression step) to produce 1 kWh of plant output. Typical energy-storage efficiencies cannot be calculated because a mixture of fuels is used. However, overall energy use is about 11,500 Btu/kWh, assuming the electricity for compression was generated at 10,000 Btu/kWh. A storage device using only electricity would have an efficiency of 87% to achieve an overall fuel use of 11,500 Btu/kWh, again assuming charging electricity is generated at 10,000 Btu/kWh. CAES system can be used on very large scales. Unlike other systems considered, large-scale CAES is ready to be used with entire power plants. Apart from the hydro pump, no other storage method has a storage capacity as high as CAES. Typical capacities for a CAES system are around 50 to 300 MW. The storage period is also the longest due to the fact that its losses are very small. A CAES system can be used to store energy for more than a year. The main drawback of CAES is probably the geological structured reliance.

11.7.3 Thermal Energy Storage

Energy can be stored as heat in appropriate materials, provided that suitable thermal insulation surrounds the storage substances. Hot rocks and fireplace bricks have served as primitive heat storage devices from ancient times. Water, rocks, and materials of high heat capacity, which are generally available, are commonly used as a storage media. Sources of energy such as solar heaters or wind generator can be used. The major difficulty is that the energy can be reutilized only as heat. Reconverting the heat energy to electrical or mechanical energy involves significant losses because of fundamental thermodynamics limitations. Storage temperature generally would be low, of course, and maximum reconversion efficiency (to mechanical or electrical form) would be on the order of few percent. Nevertheless, direct reutilization as heat can be practical, and this is done in some places. While thermal and cool storage has many applications, including thermal storage of off-peak energy in many European homes, it is not economically viable with electricity being both the energy source and the final product. The poor efficiency of converting heat to electricity is prohibitive. Thermal storage is generally only economically attractive when the energy required is heat. Thermal energy storage is ideally suited for applications such as space heating, where low quality, low temperature energy is required, but it is also possible to use thermal energy storage with conventional coal and nuclear-fired power plants, which dominates installed capacity of electricity utilities and is likely to continue to do so for the near future. Site-specific applications where heat is stored as steam and hot water at power plants have proven economic. However, retrofits of such technology into existing power plants have proven economic, but it would be difficult and costly since thermal and cool storage do not involve electricity and effectively store the thermal energy. Small water tanks are widely used for solar heat storage systems as shown in the Fig. 11-20.

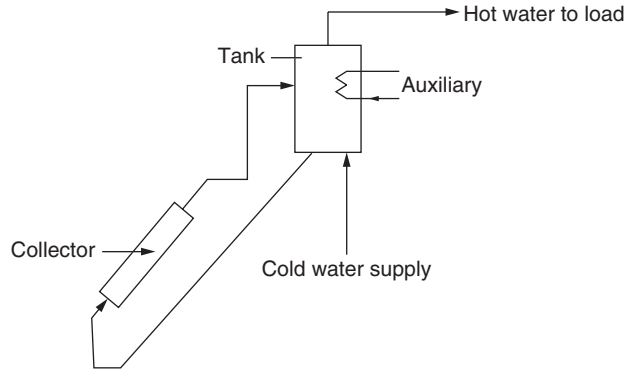


FIGURE 11-20 Hot water panel system with natural circulation.

11.7.4 Electrical Energy Storage

Superconducting Magnetic Energy Storage. Electricity (dc) can be stored in magnetic fields, wherein the energy stored is proportional to the inductance times the square of the current. An energy storage system based on magnetic would involve an ac-dc-ac converter system (like batteries) and a large coil of a superconductor (e.g., a niobium-titanium alloy). To achieve superconductivity, the conductor is maintained in a bath of liquid helium at about 1.8 K. Since there are no moving parts in the coil and electrical resistance is near zero, efficiencies can be above 90%. Energy losses occur in the converter and refrigeration system, although both can be designed to achieve high efficiency. The cost per unit of stored energy of superconducting magnetic energy storage (SMES) varies with the minus one-third power of stored energy. In other words, cost per unit of stored energy decreases by 21% for each doubling of storage capacity. In practice, therefore, very large sizes of several thousand megawatthours are required for SMES to be cost-competitive.

The basic operation of a complete SMES system is very simple and its setup is shown in Fig. 11-21. The transmission voltage from ac network is first stepped down from a few kilowatts to several hundred volts using a step-down transformer. This is then converted into dc, which is fed into the superconducting coil.

When power flows from system to coil, the dc voltage will charge up the superconducting coil and energy is stored in the coil. When ac network requires power boost, say when there are sags, spikes, and voltage and frequency instabilities, coil discharges and acts as a source of energy. The dc voltage is converted back into ac voltage through the converter.

The maximum energy stored depends on the design of the device. SMES systems are able to store upto 10 MW. However, some research believe an SMES can potentially store up to 2,000 MW. Theoretically, a coil of around 150 to 500 m radius would be able to support a load of 5000 MWh at 100 MW depending on the peak field and ratio of the coil's height and diameter.

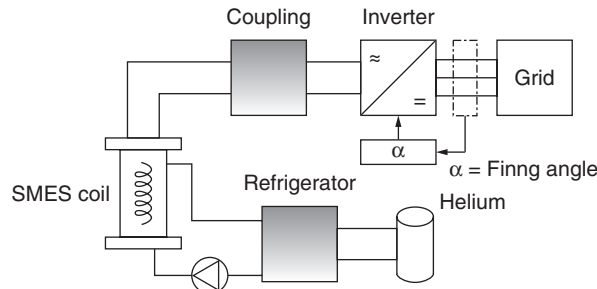


FIGURE 11-21 Basic setup of a SMES unit.

SMES is, however, attractive for applications where high power is required for very short periods. For example, a small 10- MW, 3-s experimental system was built to inhibit subsynchronous resonance in a high-voltage ac line from the state of Washington to California. Through R&D, SMES costs might be reduced sufficiently to become competitive for bulk-storage application. Ongoing research is directed to improving conductor current density and developing innovative design concepts that lower conductor support requirements. High Temperature Superconductor (HTS) coils of Ag-clad (Bi , Pb)₂ $Sr_2 Ca_2 Cu_3 O_{10+x}$ material, which can be operated with liquid nitrogen are commercially available. With successful research, issues involving the effects of magnetic fields, land use, and quality control suggest that the practical systems are commercially available and operational. A typical bidirectional converter with cryogenic arrangement is shown in Fig. 11-22.

Ultracapacitor. Capacitors are some of the most essential building blocks of electronic circuits to hold dc voltages. Based on the same principle, but on a much larger scale, it is conceivable that capacitors could be used to store energy for extended periods of time. Until some time ago, however, capacitors only managed to hold very little energy compared to a regular battery. In 1997, researchers from CSIRO developed the first supercapacitor. This is basically a capacitor which is able to hold significantly more charge using thin film polymers for the dielectric layer. The electrodes are made of carbon nanotubes. The energy density of a normal capacitor is only 0.5 Wh/kg. PET super capacitors can store 4 times more energy compared to the normal capacitor. Carbon nanotubes and polymers are practical for supercapacitors. Carbon nanotubes have excellent nanoporosity properties allowing the polymer tiny spaces to sit in the tube and act as a dielectric. Polymers have redox (reduction-oxidation) storage mechanism along with a high surface area. There are researches going on to replace carbon nanotubes with ceramics for their superconducting properties. These promising technologies introduce potential to improve the energy storage and represent a new generation of electrochemical components with very high capacitance for energy storage. A capacitor storage system with grid interface is shown in Fig. 11-23.

Supercapacitors are well suited to replace batteries in many applications. This is because at the moment their scale is comparable to that of batteries, from small ones used in cellular phones to large ones that can be found in cars. Even though supercapacitors have a lower energy density compared to batteries, they avoid many of the battery's disadvantages.

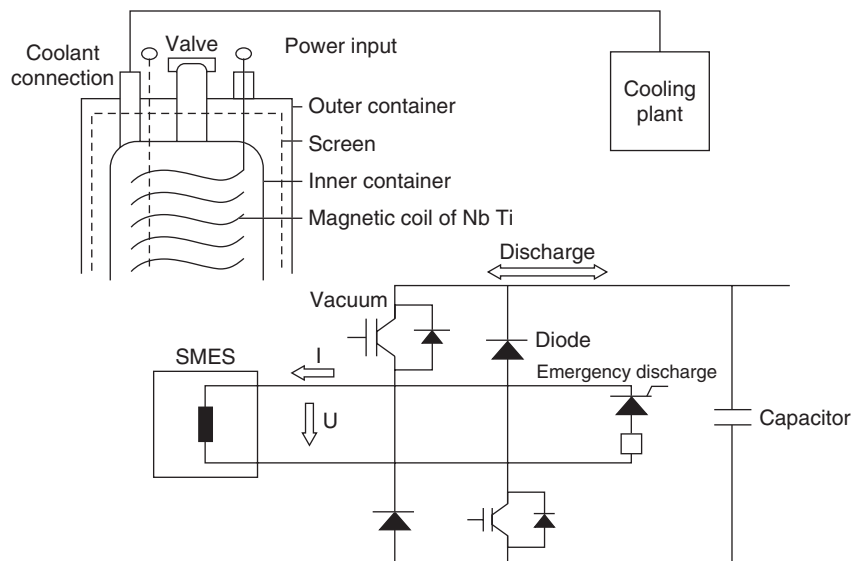


FIGURE 11-22 SMES high-temperatures system (HTS).

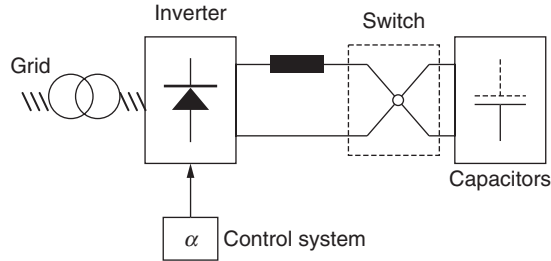


FIGURE 11-23 Capacitor storage system with grid connectivity.

Batteries have a limited number of charge/discharge cycles and take time to charge and discharge because the process involves chemical reactions with noninstantaneous rates. These chemical reactions have parasitic thermal release that causes the battery to heat up. Batteries have a limited life cycle with a degrading performance and acidic batteries are hazardous to the environment. Supercapacitors can be charged and discharged almost an unlimited number of times. They can discharge in matters of milliseconds and are capable of producing enormous currents. Hence, they are very useful in load levelling applications and fields where a sudden boost of power is needed in a fraction of a second. They do not release any thermal heat during discharge. Supercapacitors have a very long lifetime, which reduces maintenance costs. They do not release any hazardous substances that can damage the environment. Their performance does not degrade with time. Supercapacitors are extremely safe for storage as they are easily discharged. They have low internal resistances, even if many of them are coupled together. Even though they have a lower energy density, are bulkier and heavier than an equivalent battery, they have already replaced batteries in many applications due to their readiness in releasing power. Supercapacitors were initially used by the U. S. military to start the engines of tanks and submarines. Most applications nowadays are in the field of hybrid vehicles and handheld electronic devices.

In most hybrid vehicles, 42 V supercapacitors are used. General Motors has developed a pickup truck with a V8 engine that uses the supercapacitor to replace the battery. The efficiency of the engine rose by 14%. The supercapacitor supplies energy to the alternator. In rural areas, where there are voltage sags in the power grid, supercapacitors can be used to reduce the effect of fluctuations. The supercapacitor has become available to the public. A commercial supercapacitor can hold 2,500 F, release 300 A of peak current with a peak voltage handling of about 400 V. The life cycle of this supercapacitor is more than 1×10^6 charge/recharge cycles.

11.7.5 Economics of the Energy Storage Media

There is a diversity of storage technologies to store electrical energy. They are somewhat more complex to analyze than that of conventional generation systems because the number of hours of operation will dictate capital costs and its use. It is important to note that the total cost of storage system (\$/kW) is the sum of power-related costs expressed in \$/kW and the storage-related costs (\$/kW) times the required hours of storage. Thus, if long periods of storage are required, it is critical to have an inexpensive storage subsystem. On the other hand, for high-power applications with short discharge periods, low conversion cost and fast response are the key requirements. Table 11-8 outlines relative economics for the various storage systems discussed. For electric utility systems, a combination of storage systems might be optimal because of the relative costs. For example, batteries could be used for peaking (less than 5 h of storage) and CAES for intermediate duty cycle (more than 8 h of storage).

Besides economics, there are several other considerations that should be addressed before a storage system is selected for a particular application: siting restrictions, environmental impact, response time, unit size, lead time, commercial availability, and operational experience. A relative comparison of specific energy and specific power for various storages and their backup times are shown in Fig. 11-24 *a* and *b*, respectively.

TABLE 11-8 Relative Economics for Energy Storage System

Storage technology	Conversion cost, \$/kW	Storage cost, \$/kW
Lead-acid battery	Low	High
Nickel-cadmium battery	Low	Very high
Advanced battery	Low	Moderate
Pumped hydro	Moderate	Low
Underground pumped hydro	Moderate	Low to moderate
Compressed air	Moderate	Low
Superconducting magnet	Low	Very high
Flywheel	Low to moderate	Very high

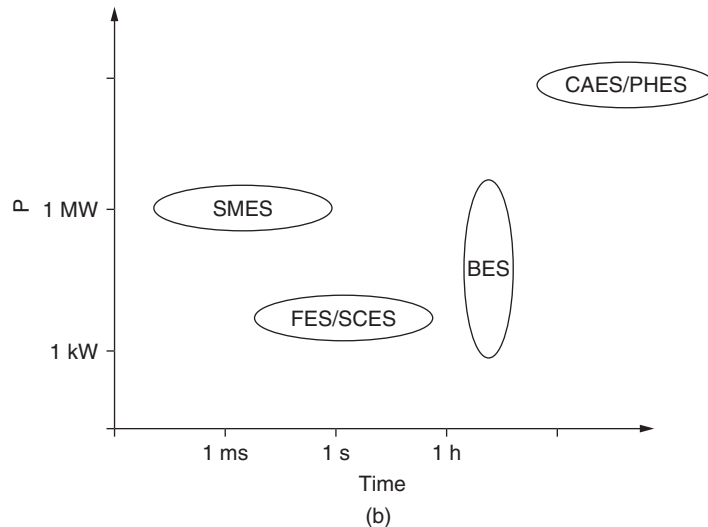
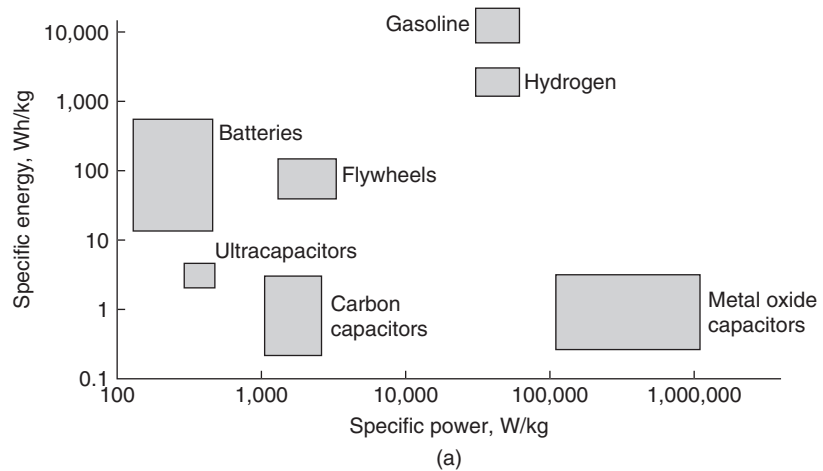
**FIGURE 11-24** Electrical power and energy storage comparison: (a) comparison of specific energy and specific power in various energy storages; (b) storage technology with its backup times.

TABLE 11-9 Performance and Cost Comparison of Energy Storage

	Batteries	Flywheel	Pumped hydro	CAES	GAS	Micro SMES	SMES	Capacitors
Efficiency	~75%	~90%	~75%	~70% + fuel	~60% + fuel	~95% + refrigeration	~95% + refrigeration	~95%
Energy Capital Cost	200 \$/kWh + replacement	800 \$/kWh	16.8 \$/kWh	10 \$/kWh	250 \$/kWh	~300 \$/kJ	Depends on size	3600 \$/kJ
Power Capital Cost \$/kW	300	220	600	425	1000	500	300	300
Fixed O & M \$/kW/yr	1.55	7.5	4.3	1.35	2.8	8	1	5% of capital
Variable O & M \$/kWh	0.5	0.4	0.43	0.1	0.1	0.5	0.1	-

Only after these entire factors are considered then the storage system be selected for any particular application. Once selected, storage systems often will be very competitive with generation technologies, provided low-cost charging energy is available.

Table 11-9 presents the most commonly used and emerging storage systems' comparison with their operating hours and efficiencies. Most storage systems have greater size and operational flexibility than the competing generation schemes and therefore should be seriously considered in any utility expansion plan and for certain utility customers.

GLOSSARY

BES-Battery energy Storage
 CAES-Compressed Air Energy Storage
 EES-Electrochemical Energy Storage
 FES-Flywheel Energy Storage
 PHES-Pumped Hydropower energy storage
 SMES-Superconducting Magnetic Energy Storage

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11.8 BATTERIES

BY ROBERT D. WEAVER AND PAUL BUTLER

11.8.1 Principles of Operation

Electrochemical Principles and Reactions. A battery is a device that converts the chemical energy contained in its active materials directly into electrical energy by means of oxidation-reduction electrochemical reactions. These types of reactions involve the transfer of electrons from one material to another. In a battery (Fig.11-25), the negative electrode or anode is the component capable of giving up electrons, that is, being oxidized during the reaction. It is separated from the positive electrode or cathode, that is, the component capable of accepting electrons and being reduced. The transfer of electrons takes place in the external electric circuit, connecting the two materials. Transfer of charge is completed within the electrolyte by movement of ions (anions and cations), not by electron flow.

The operation of a fuel cell is similar to that of a battery except that one or both of the reactants are not contained in the electrochemical cell but are fed into it from an external supply when power is desired. The fuels are usually gaseous or liquid (compared with the metal anodes generally used in batteries), and oxygen or air is the oxidant.

Components of Batteries. The basic unit of the battery is the cell. A battery consists of one or more cells, connected in series or parallel depending on the desired output voltage and capacity. The cell consists of three major components: the anode (the reducing agent or fuel), the cathode or oxidizing agent, and the electrolyte which provides the necessary internal ionic conductivity. Electrolytes are usually liquid, but some batteries employ solid electrolytes which are ionic conductors at battery operating temperatures. In addition, practical cell design requires a separator material (which serves to separate the anode and cathode electrodes mechanically), electrically conducting grid structures or materials added to each electrode to reduce internal resistance, and suitable containers.

Theoretical Cell Voltage and Capacity. The theoretical capacity (amperehours) of a battery system is determined by its active materials. The maximum electrical energy (watthours) corresponds to the free-energy change of the reaction. The theoretical voltage and specific energy ratings of a number of electrochemical systems are given in Table 11-10. The voltage is determined by the active materials selected, while the amperehour capacity is determined by the amount (weight) of available reactants. One gram-equivalent weight of material will supply 96,480 c, or 26.805 Ah, of electrical charge.

Factors Influencing Battery Voltage and Capacity. In practice, only a small fraction of a battery's theoretical specific energy is realized. As a rule of thumb, a secondary (rechargeable) battery will not attain much more than 25% of the theoretical value; claims of specific energy values significantly greater than 25% of theoretical should be viewed with appropriate caution. Refer to Table 11-10

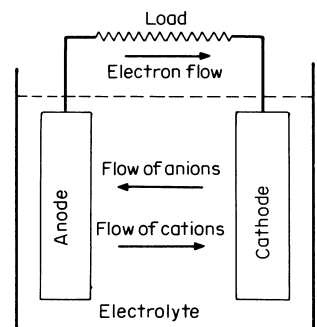


FIGURE 11-25 Electrochemical operation of a battery.

TABLE 11-10 Characteristics of Some Battery Systems

Battery type— common name	Chemical reactant		Theoretical battery		Practical battery	
	Negative electrode	Positive electrode	Voltage, V	Specific Energy, Wh/kg	Nominal voltage, V	Nominal specific energy, ^a Wh/kg
Primary						
Lecclanche	Zn	MnO ₂	1.5	260	1.2	80
Magnesium	Mg	MnO ₂	2.0	582	1.5	125
Alkaline MnO ₂	Zn	MnO ₂	1.6	380	1.3	95
Mercury-zinc	Zn	HgO	1.34	260	1.2	95
Mercurad	Cd	HgO	0.9	160	0.85	45
Silver-zinc	Zn	AgO	1.7	480	1.6	130
Li-MnO ₂	Li	MnO ₂	3.5	1000	2.7	200
Li-sulfur dioxide	Li	SO ₂	2.95	1100	2.9	250
Li-thionyl chloride	Li	SOCl ₂	3.66	1500	3.5	340
Zinc-air ^b	Zn	Air (O ₂)	1.6	1310	1.2	200
Hydrogen-oxygen fuel cell	H ₂	O ₂	1.23	3660	1.0	100
Secondary						
Lead-acid	Pb	PbO ₂	2.1	175	1.8	40
Edison	Fe	NiOOH	1.5	230	1.2	40
Nickel-cadmium	Cd	NiOOH	1.3	210	1.2	50
Silver-zinc	Zn	AgO	1.85	440	1.5	140
Lithium ion ⁱ	Li (C6)	Li0.5CoO ₂	3.9	390	2.3	110
Lithium polymer	Li	V6O13	2.8	880	2.3	150
Nickel-zinc	Zn	NiOOH	1.75	330	1.6	70
Zinc-air ^b	Zn	Air (O ₂)	1.6	1030	1.1	150
Nickel-metal hydride	H ₂ · (metals)	NiOOH	1.3	230	1.2	60
Zinc-bromine	Zn	Br ₂	1.8	430	1.0	75

Reserve									
Sea-water ^c									
Silver-zinc ^d									
Thermal ^e									
High temperature									
Sodium-sulfur ^f									
Zebra ^g									
Lithium · (aluminum)									
iron disulfide ^h									
Lithium · (aluminum)									
iron sulfide ⁱ									

^aDelivered energy when discharged at normal temperatures and rates.

^bWeight of air not considered in computation of energy.

^cWater-activated. Mass of water not included in calculation of theoretical energy.

^dAutomatically activated; high-rate discharge; 2- to 20-min rate.

^eFused salt; heat activated; high-rate discharge; <1- to 60-min discharge times; practical value includes mass of pyrotechnic heat source.

^fBeta alumina solid electrolyte, sodium polysulfides as fused-salt electrolyte, 350°C operation.

^gSimilar to sodium/sulfur; uses NaAlCl₄ as fused-salt electrolyte and NiCl₂ as positive reactant. Temperature of operation can be as low as 200°C.

^hFused-salt electrolyte, 400°C operation.

ⁱSpecific energy values based on 0.5 Li per LiCoO₂, Li-to-C ratio taken as 1:6.

for representative voltages and specific energies for practical batteries. There are many reasons for the reduction. The weights of nonreactive components (e.g., containers, separators, electrolyte) will degrade the specific energy and performance of any battery system. There may be other, less obvious, factors as well. Consider a "room temperature" system as an example. If, as is so often the case, its performance, because of self-discharge, is degraded significantly by a modest increase in temperature, and if the application is one involving high power, such as use in an electric vehicle, a major weight penalty must be added for the heat-exchange system required to keep temperature below a practical limit. There may well be other temperature-related considerations; an inability to produce required power when below room temperature may require heating prior to use with attendant delays and weight penalties. Other factors influencing the voltage and capacity of a battery are as follows:

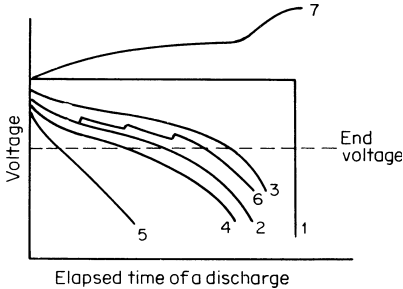


FIGURE 11-26 Battery-discharge characteristics.

Voltage Level. When a battery is discharged, its voltage is lower than the theoretical voltage. The difference is caused by IR losses due to cell resistance and by polarization of the active materials during discharge. This is illustrated in Fig. 11-26. The theoretical discharge curve of a battery is shown as curve 1. In this case, the discharge of the battery proceeds at the theoretical voltage until the active materials are consumed and the capacity fully utilized. The voltage then drops to zero. Under actual conditions, a typical discharge curve is similar to curve 2. The initial voltage is lower than theoretical, and it drops off as the discharge progresses.

The Current Drain of the Discharge. As the current drain of the battery is increased, the IR loss increases, the discharge is at a lower voltage, and the discharge duration is usually reduced (curve 5). At extremely low current drains, it is possible to approach the theoretical capacities (in the direction of curve 3). In a very long discharge period, the chemical degradation during the discharge becomes a factor and causes a reduction of capacity.

Voltage Regulation. The voltage regulation required by the equipment is most important. As is apparent by the curves in Fig. 11-26, design of equipment to operate to the lowest possible end voltage results in the highest capacity and longest service life. Similarly, the upper voltage limit of the equipment should be established to take full advantage of the battery characteristics. In some applications, where only a narrow voltage range can be tolerated, voltage regulators may have to be employed to take full advantage of the battery's capacity. If a secondary battery is used in conjunction with another energy source, which is permanently connected in the operating circuit, allowances must be made for the voltage required to charge the battery, as illustrated in curve 7, Fig. 11-26. The maximum voltage available from the charger must exceed the maximum battery charge voltage.

11.8.2 Primary Batteries

General. A number of different types of primary (nonrechargeable) batteries are used widely in civilian, industrial, and military applications. They are a convenient, usually relatively inexpensive, lightweight source of power for portable electric devices. The general advantages of primary batteries are reasonably good shelf life, high energy densities at low to moderate rates, little, if any, maintenance, and ease of use. Typical characteristics and applications of these batteries are shown in Tables 11-11 and 11-12.

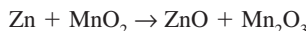
Leclanche Cell (Zn-MnO_2). The Leclanche or carbon-zinc dry cell, known for over 100 years, is still the most widely used of all the dry-cell batteries because of its low cost, reliable performance, and ready availability. Cells and batteries of many sizes and characteristics have been manufactured to meet the requirements of a wide variety of applications. Characteristics of typical cells are given in Table 11-12.

Composition. The Leclanche cell uses a zinc anode, a manganese dioxide cathode, and an electrolyte of ammonium chloride and zinc chloride dissolved in water. Powdered carbon (acetylene

TABLE 11-11 Major Characteristics and Applications of Primary Batteries

System	Characteristics	Applications
Zinc-carbon (Leclanche) (Zn-MnO ₂)	Popular common low-cost primary battery, available in variety of sizes	Flashlight, portable radios and electronics, toys, novelties, instruments, etc.
Magnesium (Mg-MnO ₂)	High-capacity primary battery, long shelf life	Military receiver-transmitters, aircraft emergency transmitters
Mercury (Zn-HgO)	Highest capacity (by volume) of conventional types, flat discharge, good shelf life	Hearing aids, medical (heart pacers), photography, detectors, receiver-transmitters, military sensor and detection equipment
Alkaline (Zn-alkaline electrolyte-MnO ₂)	Good low-temperature and high-rate performance, moderate cost	Cassettes and tape recorders, calculators, radio, and TV—popular for high-drain primary-battery application
Silver-zinc (Zn-AgO)	Highest capacity (by weight) of conventional types, flat discharge, good shelf life	Hearing aids, photography, electric watches, missiles and space application (larger sizes)
Lithium (lithium-SO ₂)	New battery system—recent development; highest-performance primary battery, excellent low-temperature performance, long shelf life	Will have wide, general-purpose application when available; first uses will be military and special civilian applications needing high-capacity and low-temperature performance
Solid electrolyte	Extremely long shelf life, low-power battery	Medical electronics, memory circuits, fusing

black) is mixed with the depolarizer to improve conductivity and retain moisture. As the cell is discharged, the zinc is oxidized and the manganese dioxide reduced. The overall cell reaction is



Construction. The Leclanche cell is made in many shapes and designs, but in two basic constructions: cylindrical and flat. Similar chemical ingredients are used in both constructions. In the common cylindrical cell (Fig. 11-27) a zinc can serves as the cell container and anode. The manganese dioxide is mixed with acetylene black and solid ammonium chloride, wet with a zinc chloride–ammonium chloride electrolyte, and shaped in the form of a bobbin. A carbon rod is inserted into the bobbin. The rod serves as a current collector and is porous enough to permit the escape of gases, which accumulate in the cell, without allowing leakage of electrolyte. The separator is a cereal paste, also wet with electrolyte, which physically separates the two electrodes and provides the means for ion transfer through the electrode. In the newer “paper-lined” cell, an absorbent kraft paper is used as the separator. This provides thinner separator spacing and lower internal resistance.

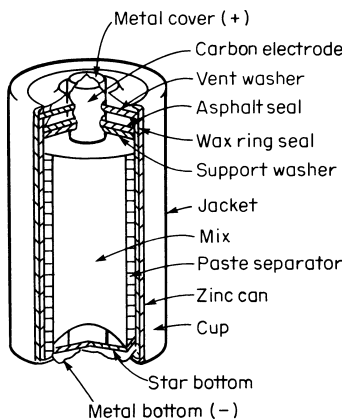
Another cylindrical cell is the “inside-out” construction shown in Fig. 11-28. In this cell, an injection-molded, impervious, inert carbon wall serves as the container of the cell and as the current collector. The zinc anode, formed in the shape of vanes to increase its surface area, is located inside the cell and surrounded by the cathode mix. This ensures efficient zinc consumption and, since zinc is not used as a container, a high degree of leakage resistance.

The flat-cell construction is illustrated in Fig. 11-29. In this cell, carbon is coated on a zinc plate to form a duplex electrode—a combination of the zinc of one cell and the carbon of the adjacent one. The flat cell has a higher energy-to-volume ratio, since the rectangular shape utilizes the available volume better than does the cylindrical cell.

Zinc Chloride Cell. A modification of the Leclanche cell is the zinc chloride electrolyte cell. The construction is similar to the conventional carbon-zinc cell, but the electrolyte contains only zinc

TABLE 11-12 Approximate Service Capacity of American National Standards Institute Sizes of Cylindrical and Flat Carbon-Zinc Cells at Various Current Drains

USASI cell capacity, size	Starting drain, mA	Service capacity, h	USASI cell size	Starting drain, mA	Service capacity, h	USASI cell size	Starting drain, mA	Service capacity, h
N	1.5	275	G	15	820	F24	1	475
	7.5	52		75	150		5	150
	15	24		150	65		10	72
AAA	2	290	6	50	700	F30	1.3	275
	10	45		250	150		6.5	40
	20	17		500	70		13	16
AA	3	350	F15	0.4	210	F40	1.3	450
	15	40		2	30		6.5	108
	30	15		4	8		13	52
B	5	420	F12	0.5	435	F60	2	190
	25	65		2.5	103		10	40
	50	25		5	51		20	15
C	5	430	F17	0.6	710	F70	3	550
	25	100		3	155		15	150
	50	40		6	75		30	65
D	10	500	F20	0.7	210	F80	3	600
	50	105		3.5	35		15	165
	100	45		7	12		30	72
E	15	400	F22	0.8	475	F90	3	770
	75	70		4	98		15	200
	150	30		8	49		30	90
F	15	520	F25	1	500	F100	5	1000
	75	105		5	105		25	260
	150	45		10	45		50	110

**FIGURE 11-27** Cross section of a Leclanche cylindrical cell.

chloride, without the saturated solution of ammonium chloride. The zinc chloride cell is a high-performance cell with improved high-rate and low-temperature performance, and a reduced incidence of leakage. A comparison of the performance of the zinc chloride cell with the conventional cell is presented in Fig. 11-30.

Magnesium Dry Cells ($Mg-MnO_2$). A magnesium dry cell has two main advantages over the zinc-carbon cell: twice the capacity or service life of an equivalently sized zinc cell and the ability to retain this capacity during storage, even at elevated temperatures (Fig. 11-31). The construction of the magnesium dry cell is similar to the cylindrical carbon-zinc cell except that a magnesium alloy is used instead of zinc. The cathode consists of an extruded mix of manganese dioxide, acetylene black (to provide conductivity and moisture absorbency), magnesium perchlorate electrolyte, barium and lithium chromate as corrosion inhibitors, and magnesium hydroxide as a buffering agent to improve storage life. The

degree of "wetness", or amount of water, is critical because water participates in the anode reaction and is consumed during discharge. A carbon rod serves as the cathode current collector. The separator is an absorbent kraft paper as in the paper-lined structure. Sealing of the magnesium cell is critical, since it must be tight to retain cell moisture during storage and also provides a means for the

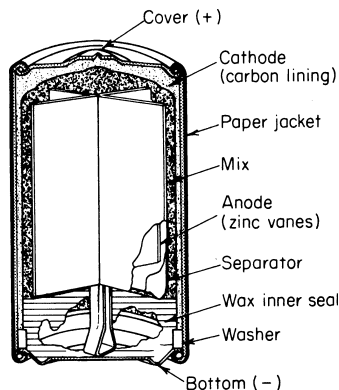


FIGURE 11-28 Cross section of a Leclanche "inside-out" cell.

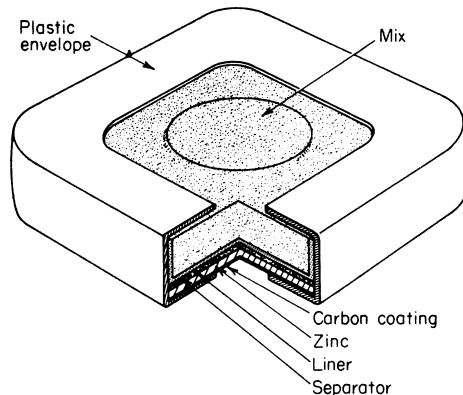
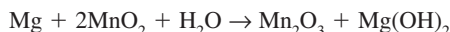


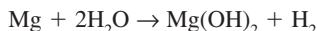
FIGURE 11-29 Leclanche flat cell.

escape of hydrogen gas which forms as the result of a parasitic reaction during the discharge of the battery. This is accomplished by a mechanical vent—a small hole in the plastic top seal washer under a retainer ring, which is deformed under pressure, releasing the excess gas. Magnesium batteries have not been fabricated successfully in flat-cell designs.

The overall reaction of the Mg-MnO₂ cell is



At the same time, hydrogen is generated as the result of the parasitic magnesium corrosion reaction:



The efficiency of the magnesium anode during a typical discharge is about 70%. Considerable heat is generated during the discharge of a magnesium battery owing to the exothermic side reaction and the *IR* loss resulting from the difference between the theoretical and operating voltages. This heat can be used to advantage at low ambient temperatures to maintain the battery at a warmer temperature.

The good shelf life of the magnesium cell results from a protective film that forms on the inside of the magnesium can, preventing corrosion. This film, however, is responsible for a voltage "delay"—a delay in the cell's ability to deliver full output voltage after it has been placed under load (Fig. 11-32).

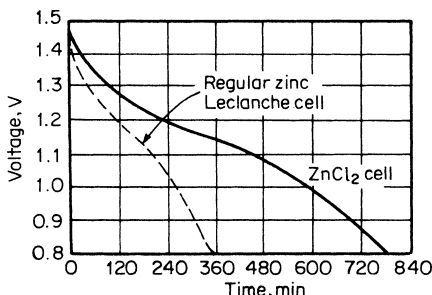


FIGURE 11-30 Comparative performance of zinc chloride and Leclanche cells.

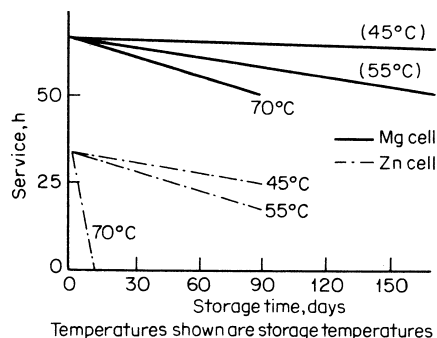


FIGURE 11-31 Comparison of service life vs. storage time of magnesium and Leclanche cells.

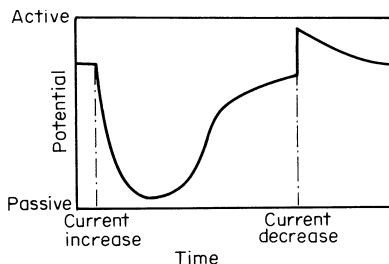


FIGURE 11-32 Voltage delay characteristics of magnesium cells.

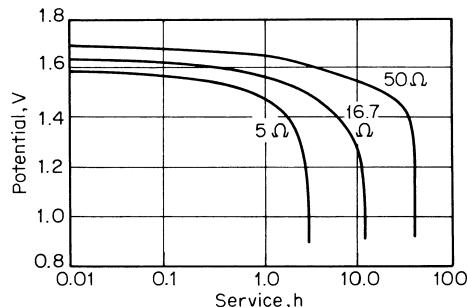


FIGURE 11-33 Discharge curves of magnesium cells (A size, 20°C).

This delay is usually less than 0.3 s, but is longer for discharges at low temperatures and high current drains and after prolonged storage at high temperatures.

Typical discharge curves are given in Fig. 11-33. The magnesium battery is less sensitive to discharge rate than the carbon-zinc cell. The performance of the magnesium cell for various discharge rates and temperatures is shown in Fig. 11-34.

While successful in military use, the magnesium battery has not found wide commercial use. This is due to the fact that the magnesium battery loses its excellent storage ability after being partially discharged, and hence is unsatisfactory for long-term intermittent use. Other influencing factors are the higher unit cell voltage and the evolution of hydrogen and heat on discharge which present a potential safety hazard.

Zinc-Mercuric Oxide Cells (Zn-HgO). The zinc alkaline-mercuric oxide battery is noted for its high capacity per unit volume, a relatively constant output voltage during its discharge, and good storage characteristics.

Composition. The zinc-mercuric oxide cell uses amalgamated zinc as the anode, mercuric oxide (mixed with 5% to 10% graphite) as the cathode, and potassium hydroxide as the electrolyte. A saturated solution of zinc oxide is added to the electrolyte to retard the corrosion of zinc, minimize the production of hydrogen, and improve the stability of the cell.

The overall chemical reaction during discharge is

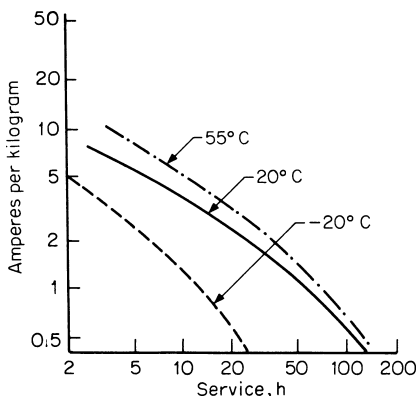
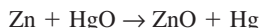


FIGURE 11-34 Service capacity of magnesium cell.

The amperehour capacities of the mercuric oxide cathode and the zinc anode are equalized or balanced, and on completion of the cell's discharge, no residual unoxidized zinc remains. Without this feature, the zinc would continue to react, generating hydrogen gas in the cell.

Construction. The zinc-mercuric oxide cell is manufactured in three basic structures: the wound-anode type, the flat-pressed powdered cathode and anode type, and the cylindrical pressed powdered electrode type.

The three types of structures are shown in Fig. 11-35. All constructions use a steel can, which does not take part in the electrochemical reaction and is not consumable, for the cell container. In the wound-anode type, the anode is composed of a corrugated zinc strip with an absorbent paper wound in an offset manner so

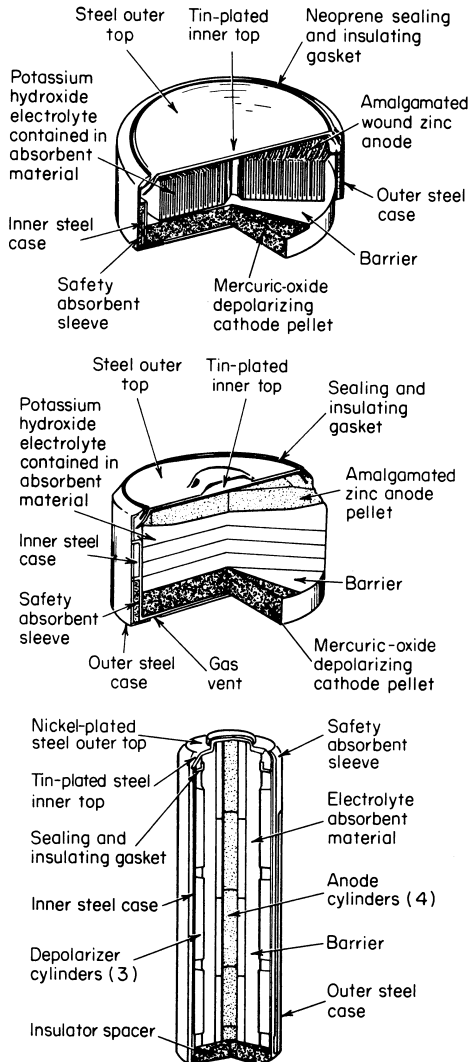


FIGURE 11-35 Zinc-mercuric oxide cell structures (left) and characteristics (right).

Type No.	Max. diam., cm	Height, cm	Weight, g	Rated capacity, mAh
RM 640	1.587	0.965	9.68	360
RM 3	2.498	1.37	22.56	1,500
RM 1438	3.71	1.003	36.22	2,700
RM 1450	3.71	1.36	51.80	4,500
RM 2550	6.58	1.394	165.20	13,000

Type No.	Max. diam., cm	Height, cm	Weight, g	Rated capacity, mAh
RM 312	0.87	0.34	0.56	36
RM 575	1.143	0.33	1.4	100
RM 675	1.143	0.54	2.24	160
RM 630	1.549	0.58	4.76	350
RM 640	1.574	1.104	7.84	500
RM 4R	3.02	1.66	40.88	3,400

Type No.	Max. diam., cm	Height, cm	Weight, g	Rated capacity, mAh
RM 24	1.0	4.396	14.0	900
RM 601	1.59	2.857	34.16	1,800
RM 3R	2.489	1.651	28.56	2,200
RM 502	1.358	4.90	30.44	2,400
RM 401	1.133	2.844	11.20	800
RM 1R	1.579	1.638	12.04	1,000
RM 12R	1.519	4.959	30.88	3,600
RM 42R	2.922	6.032	148.33	14,000

that it protrudes at one end and the zinc protrudes at the other end. The zinc is amalgamated with 10% mercury and the paper impregnated with the electrolyte, which causes it to swell and produce a positive contact pressure. The cathode is a pellet made of powdered mercuric oxide and graphite which is pressed into the steel can. An absorbent KOH-resistant separator is placed between the two electrodes. The cell has a crimped seal; the can is separated from the top by an insulating neoprene or plastic grommet.

In the pressed-powder cells, the zinc powder is amalgamated and pressed into a pellet with sufficient porosity to allow electrolyte impregnation. A double-can structure is used in the larger-sized cells as a safeguard. Under excessive gas pressures, the compression of the upper part of the grommet by internal pressure allows the gas to escape into the space between the two cases. A paper tube surrounds the inner can so that any liquid carried by the discharging gas will be absorbed, maintaining a leak-resistant structure. Release of the excess gas pressure reveals the cell.

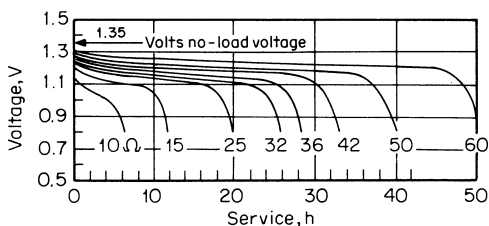


FIGURE 11-36 Discharge curves of zinc-mercuric oxide cells.

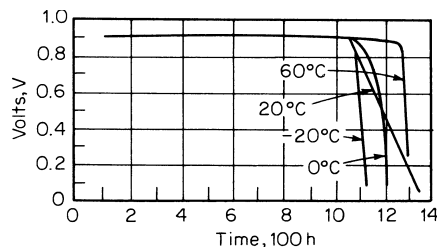


FIGURE 11-37 Discharge curves of cadmium-mercuric oxide cells.

The cylindrical and button cells are variations of the pellet design. The button cell uses a gelled electrolyte to reduce electrolyte leakage further. The mechanical and electrical specifications of representative cells of each of the three constructions are given in Fig. 11-35.

Voltage. The open-circuit voltage of the mercury cell is 1.35 V and is reproducible within 0.001 V. On discharge, the cell is characterized by a very flat discharge as shown in Fig. 11-36. The cutoff voltage usually is 0.9 to 1.0 V per cell.

Cadmium-Mercuric Oxide Cell (Cd-HgO). The substitution of cadmium for zinc results in a very stable system with a predicted shelf life of up to 10 years, as well as performance at low temperatures (Fig. 11-37). The watt-hour capacity of this cell, because of its lower voltage, is about 60% of zinc-mercuric oxide cell capacity. In design, the cadmium-mercuric oxide cell is similar to the zinc-mercuric oxide cell. These mercuric-oxide systems (Zn and Cd) are being evaluated because of environmental concerns.

Zinc-Silver Oxide Cell (Zn-AgO). The primary zinc alkaline-silver oxide cell is similar in design to the small zinc-mercuric oxide button cell but uses silver oxide in place of mercuric oxide. Cells range in capacity up to 200 mAh for use at 50-h and lighter loads. The silver oxide cell has an open-circuit voltage of 1.6 V and operates about 0.2 V higher than the mercuric oxide cell. Typical discharge curves for this cell are given in Fig. 11-38. The silver oxide cell has a higher energy density (on a weight basis) and is less sensitive to a reduction in ambient temperature than the mercuric oxide cell. At the design loads, the cell will deliver about 70% of its 20°C performance at 0°C and 35% at -20°C. These characteristics make this battery desirable for use in hearing aids, photographic applications, and electronic watches.

Alkaline-MnO₂ Cell (Zn-MnO₂). The zinc alkaline-MnO₂ cell uses the same electrochemically active materials, zinc and manganese dioxide, as the Leclanche cell, but differs in construction and in the use of highly conductive potassium hydroxide electrolyte which results in a lower internal resistance. The advantage on low-rate or intermittent discharge is marginal, but on high- and continuous-drain conditions, the alkaline cell can deliver from 2 to 10 times the ampere-hour capacity of the Leclanche cell. Its performance at low temperatures is superior to other commercially available dry batteries.

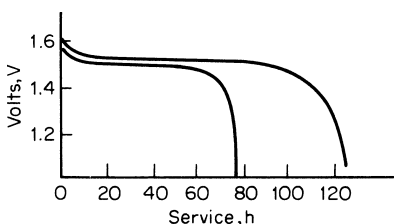
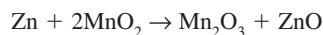


FIGURE 11-38 Discharge curves of zinc-silver oxide cells.



The electrolyte undergoes no change during the discharge, maintaining its high conductivity throughout the cell's life. It thus differs from the Leclanche cell, whose resistance increases during the discharge.

Construction. The principal features of the Zn-MnO₂ cell are the manganese dioxide cathode of high density, a zinc anode of high surface area, and the highly conductive potassium hydroxide electrolyte. As illustrated in Fig. 11-39, the MnO₂, mixed with graphite or carbon black, is pressed against the inner surface of the can, which serves as the cathode current collector. The anode is centrally located and consists of a mixture of granular or powdered zinc, which is amalgamated to reduce hydrogen evolution, and the electrolyte. In some designs, a gelling agent is used to immobilize the electrolyte and minimize leakage. A highly absorbent, chemically inert material separates the electrodes.

Voltage. The open-circuit voltage of the alkaline-MnO₂ cell is 1.5 V. Its discharge is similar to the Leclanche cell, but it is superior at the heavier discharge loads. Typical discharge curves are given in Fig. 11-40.

Service Life. At light loads, the service life of the alkaline cell is about the same as the Leclanche. However, its service capacity remains relatively constant with increasing load and is much superior to the Leclanche at higher current drains. The performance of the alkaline cell for various discharge rates and temperatures is shown in Fig. 11-41.

Effect of Temperature. The alkaline-MnO₂ cell performs well at low temperatures, excelling over the best Leclanche cells. The cell operates to temperatures as low as -40°C.

Shelf Life. The shelf life of the alkaline-MnO₂ cell is moderately superior to the Leclanche cell. Capacity retention is about 90% after 1 year of storage at 20°C.

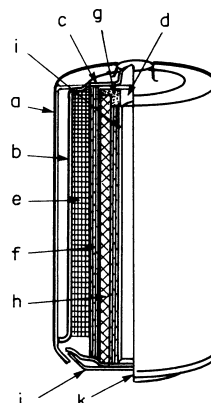


FIGURE 11-39 Construction of alkaline-MnO₂ cells: (a) outer nickel-plated can; (b) tube adapter; (c) inner gold-plated can; (d) insulator disk; (e) depolarizer; (f) outer absorbent with barrier; (g) insulating ring; (h) anodes; (i) inner absorbent; (j) molded double top; (k) clear plastic dielectric jacket. Electrolyte not shown. (Duracell.)

Lithium Primary Batteries. The lithium battery has a number of advantages over other primary-battery systems. Lithium is an attractive anode because of its reactivity, light weight, and high voltage; cell voltages range between 2 and 3.6 V, depending on the cathode material.

The advantages of the lithium battery include high specific energy and energy density, on the order of 250 Wh/kg and 400 Wh/dm³, respectively; high power density; flat discharge characteristics; excellent service over a wide temperature range, down to -40°C or below; and good shelf life (up to 5 years without refrigeration is anticipated).

Nonaqueous solvents must be used as the electrolyte because of the reactivity of lithium with aqueous solutions. Organic solvents, such as acetonitrile and propylene carbonate, and inorganic solvents, such as thionyl chloride, are typical. A compatible solute is added to provide the necessary

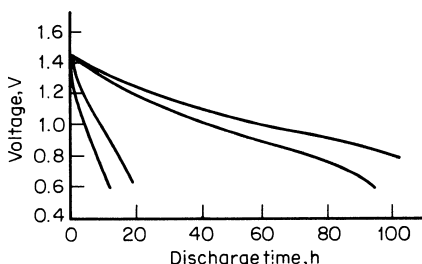


FIGURE 11-40 Discharge curves of an alkaline-MnO₂ cell at 20°C.

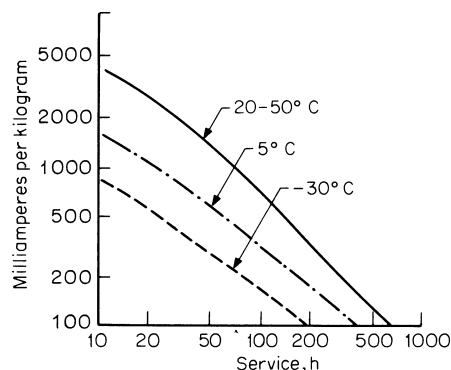


FIGURE 11-41 Service capacity of an alkaline-MnO₂ cell.

electrolyte conductivity. A number of different materials—sulfur dioxide, carbon monofluoride, vanadium pentoxide, and copper sulfide—are used as the active cathodes.

Lithium–Sulfur Dioxide Cell. One advanced lithium primary cell uses sulfur dioxide for the cathode material and an electrolyte consisting of acetonitrile and lithium bromide. The cell reaction is

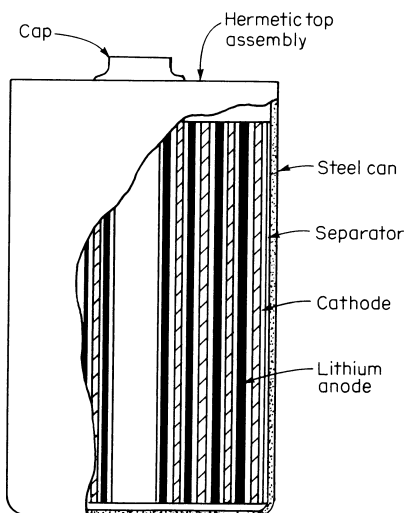


FIGURE 11-42 Cross section of a cylindrically wound Li-SO₂ cell.

The cell is typically fabricated in a cylindrical structure as shown in Fig. 11-42. A “jellyroll” construction is used, made by spirally winding strips of lithium ribbon, a polypropylene separator, and the cathode electrode (a Teflon-carbon mix pressed on an aluminum screen). This design provides the high surface area and low cell resistance necessary to obtain high-current and low-temperature performance. The roll is inserted in a steel container which is electrically connected to the anode. The cathode, in turn, is connected to its terminal and the cell hermetically sealed. The electrolyte-depolarizer mixture (70% SO₂) is added through a temporary opening in the cell to an SO₂ pressure of about 4 atm. The critical manufacturing operations are carried out in dry rooms or dry boxes to minimize the moisture content of the cell.

The good shelf life of the lithium-SO₂ cell is attributed to the protective film formed by the initial reaction of lithium and SO₂, which prevents further reaction or loss of capacity during stand. During discharge, the SO₂ is depleted and the cell pressure reduced. The discharge is generally terminated by the deactivation of the carbon electrode by blocking the active area from precipitation of the discharge product.

The performance characteristics of the Li-SO₂ cell are given in Figs. 11-43 through 11-46. Figure 11-43 shows typical discharge curves for the cell at various discharge loads. The high cell voltages and flat discharge curves shown are characteristic of this cell.

Figure 11-44 presents the performance of the Li-SO₂ cell at various temperatures and discharge rates. The superior low-temperature performance (over 60% of the normal-temperature performance available at –30°C) is noteworthy. Figure 11-45 illustrates the shelf life of the lithium cell. Although

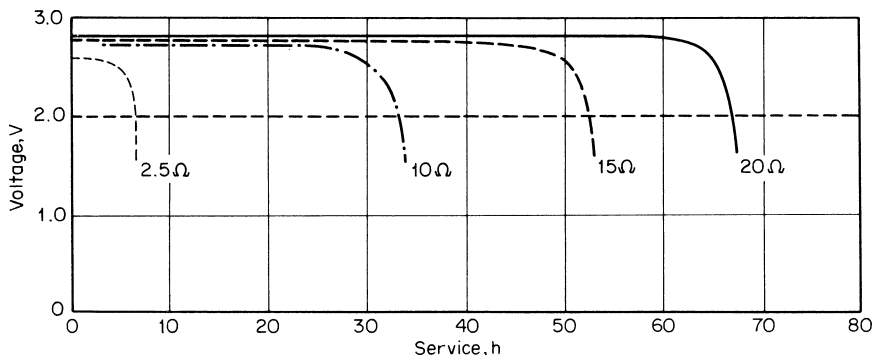


FIGURE 11-43 Typical discharge curves of Li-SO₂ cell at 20°C at various loads.

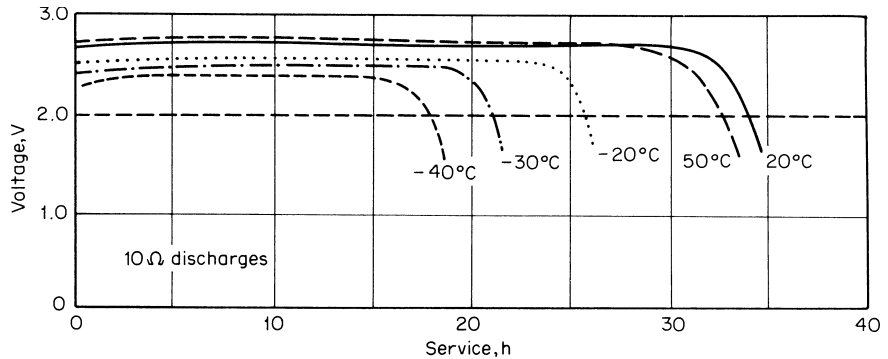


FIGURE 11-44 Effect of temperature on performance of Li-SO₂ cells (D size).

very long-term storage has not been demonstrated experimentally, the data suggest a long-shelf-life capability even at high temperatures, particularly with newer cell designs.

Special attention must be given to the design and use of the lithium battery, since it contains materials that are potentially flammable and toxic. Properly designed cells are equipped with safety vents which release SO₂ when the cells reach high temperatures and pressures, thus preventing explosive damage.

The lithium battery can deliver unusually high current. Since high internal temperatures can develop from continuous high current drain, short circuiting, or inadvertent internal cell shorts, such use must be avoided. It is advisable to equip batteries with fuses to protect against short circuiting.

Charging lithium-SO₂ cells may result in explosion of cells (even those which are equipped with safety vents) and should not be attempted. Similarly, cells or groups of cells should not be connected in parallel without diode protection to prevent one group of

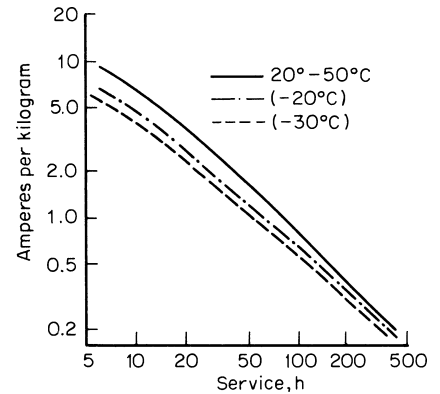


FIGURE 11-45 Service capacity of Li-SO₂ cells at various temperatures.

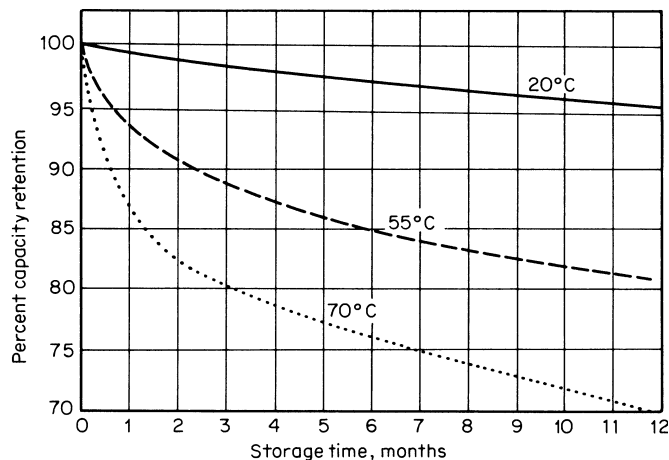


FIGURE 11-46 Shelf life of Li-SO₂ cell at different storage temperatures.

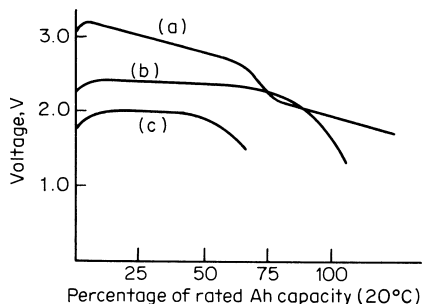


FIGURE 11-47 Typical discharge curves of lithium-solid cathode cells: (a) vanadium pentoxide, 8-h rate, 20°C; (b) carbon monofluoride, 20-h rate, 20°C; (c) carbon monofluoride, 20-h rate -20°C.

cells from charging the other. Forced discharging, which could occur with cells that are connected in series or to an external power supply, also may result in venting and/or explosion. Currently, special procedures govern the transportation, shipment, and disposal of lithium batteries. While it requires special handling and design, the many advantages of the lithium cell result in increasing use of this battery in military and civilian areas.

Other Lithium-Organic Electrolyte Cells. A number of other cathode materials, mostly solid, have been developed for lithium primary cells. Cells using these solid cathodes have the advantage of being nonpressurized but do not have the high current capability of the SO_2 system.

Some cells are specifically designed for low-rate applications, using “bobbin”-type constructions. These cells deliver higher energy outputs and should provide safe operation, since they are self-limiting in energy and current output. Typical discharge curves for the carbon monofluoride and vanadium pentoxide cells are shown in Fig. 11-47.

Inorganic Electrolyte Cells. Certain nonaqueous inorganic liquids, such as thionyl chloride (SOCl_2) and sulfuryl chloride (SO_2Cl_2), also are capable of forming a passivating film on the lithium anode, similar to that in SO_2 , and can be used both as the electrolyte solvent and as the active cathode material. A commonly used solute is LiAlCl_4 . Cells made with these components are similar in construction to the Li-SO_2 cell but are not pressurized at room temperature because of the lower vapor pressure of the thionyl chloride. The Li-SOCl_2 cells also operate at approximately 0.5 V higher than the comparable Li-SO_2 cell. Figure 11-48 compares the discharge curves of the two batteries and illustrates the higher voltage and energy output of the thionyl chloride cell. The cells exhibit good shelf life, but the passivating protective film that forms, particularly at high-temperature storage, is not readily penetrated, and excessively long voltage delays occur, especially at high-rate and low-temperature discharges. Lithium-thionyl chloride cells are available in a range of capacities from 1.4 to 8,000 Ah. Corresponding specific energy ranges from 240 to 450 Wh/kg at

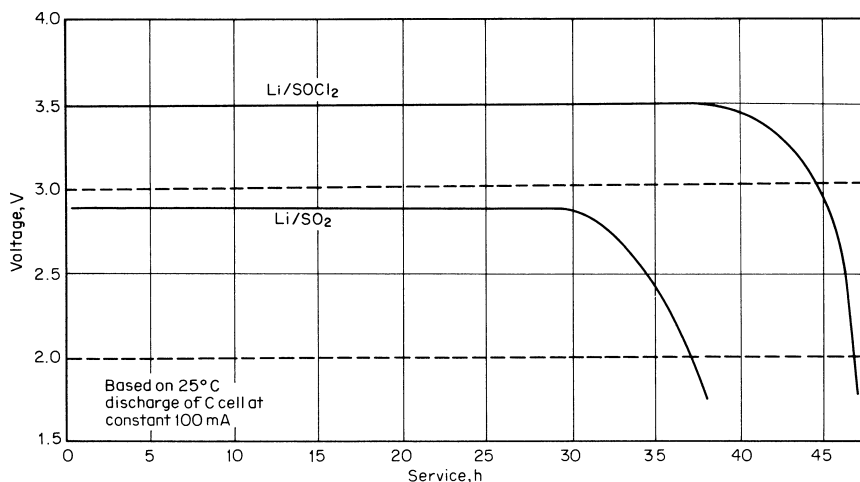


FIGURE 11-48 Discharge curves of Li-SOCl_2 and Li-SO_2 cells.

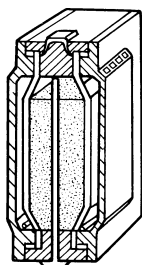


FIGURE 11-49
Construction of
primary zinc-air
cell. (Duracell.)

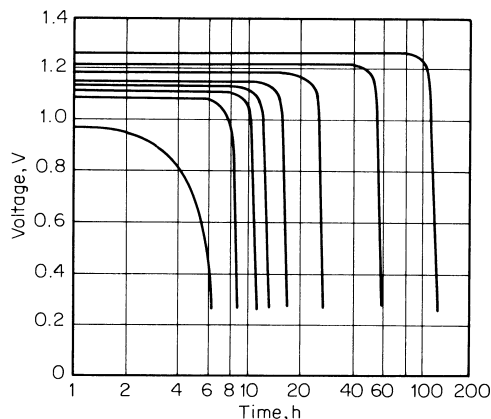


FIGURE 11-50 Typical discharge curves of zinc-air primary cells. (Duracell.)

rates of about 10 days. The cells display safety characteristics that reflect engineering to accommodate the high-energy nature of the reactants. A representative cell reaction is



Zinc-Air Cells. Primary batteries using air as the depolarizer can deliver high energy densities, since they do not contain active cathode material. Zinc-air batteries, using bulky zinc anodes, a carbon-air cathode, and potassium hydroxide electrolyte, constructed in heavy-glass or hard-rubber containers, had been used successfully for many years in railway signals and similar applications. They were noted for their high energy densities but low power output capability. Lower-capacity zinc-air batteries, up to the 20-Ah size, are now being developed, using thin Teflon-coated fuel cell-type electrodes. These new structures have high specific energy, on the order of 220 Wh/kg, and are capable of moderately high current drains.

Construction. A typical construction of the primary zinc-air cell is shown in Fig. 11-49. It consists of a high-surface-area, gelled zinc anode, fabricated by pressing zinc granules with a gelled potassium hydroxide electrolyte, and a teflonated air cathode made of a low-cost, non-noble-metal catalyst. Cylindrical-shaped and button cells also have been designed. Effective sealing is essential in this construction to prevent electrolyte leakage. The cells are stacked to form a battery; space must be left between each cell for air circulation.

Performance Characteristics. The zinc-air battery is best suited for continuous, moderate-drain discharges at temperatures between -20 and $+35^\circ\text{C}$. Intermittent operation usually results in a loss of capacity due to the drying out of the cell. Since the cell depends on oxygen from the air for its operation, differences in performance occur with variation in air circulation. Figure 11-50 shows typical curves for continuous discharge at 20°C . The flat discharge is characteristic of this cell. Figure 11-51 shows the energy output of the zinc-air battery at various temperatures. In addition to the reduction of service life, the average voltage decreases with decreasing discharge temperature.

Primary zinc-air cells must be stored in sealed bags after manufacture to maximize storage life. Limits of storage as well as the integrity and leak resistance of the cell seal

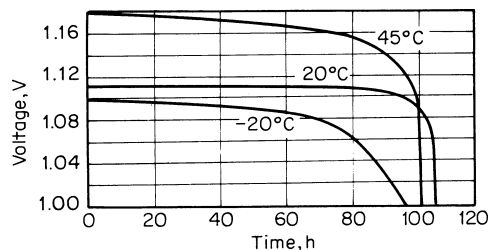


FIGURE 11-51 Voltage vs. time curve of zinc-air cell at various temperatures. (Duracell.)

TABLE 11-13 Characteristics of Solid Electrolyte Cells

System	Cell voltage, V	At 100-h rate	
		Wh/dm ³	Wh/kg
Ag/RbAg ₄ I ₂	0.66	40–80	15–25
Li/LiI(Al ₂ O ₃)/PbI ₂ , Pb	1.9	100–200	35–70
Li/LiI(Al ₂ O ₃)/PbI ₂ , PbS, Pb	1.9	300–500	75–150
Li/LiI/I ₂ (poly-2-vinylpyridine)	2.8	250–500	120–180

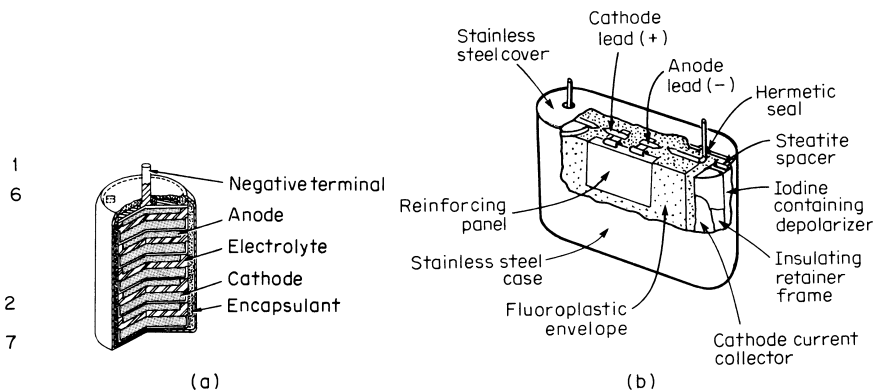
have yet to be determined. Once the packaging has been removed, the battery should be put into service shortly thereafter, since moisture loss results in dry-out and reduced capacity.

Solid Electrolyte Batteries. Most batteries depend on the ionic conductivity of liquid electrolytes for their operation. The solid electrolyte batteries depend on the ionic conductivity of an electronically nonconductive salt in the solid state as, for example, Ag⁺ ion mobility in silver iodide. Cells using these solid electrolytes are low-power (microwatt) devices but have an extremely long shelf life and the capability of operating over a wide temperature range. The absence of liquid eliminates corrosion and gassing and permits the use of a hermetically sealed cell. The solid electrolyte batteries are used in medical electronics (in devices such as heart pacemakers), for memory circuits, and for fusing and other such applications requiring a long-life, low-power battery.

Several types of solid electrolyte batteries are being marketed using different solid electrolytes and active materials. The characteristics of several of the available types are summarized in Table 11-13. Of special significance are the high energy densities (5 to 10 Wh/in³) achieved with the Li-anode solid electrolyte battery. Typical construction of solid electrolyte cells is shown in Fig. 11-52. The design features a sealed structure to exclude moisture and maintain a high-density, void-free package.

The discharge curves for various solid electrolyte cells at 25°C are given in Fig. 11-53. Since the batteries are designed primarily for low current drain, continuous discharge at high rates is not practical. The energy density and power density also are dependent on the operating temperature. A significant characteristic of the solid electrolyte battery is its long shelf life. Projections based on limited tests (1 to 2 years) predict a shelf life exceeding 15 years at 20°C. Figure 11-54 shows the projected capacity retention at various storage temperatures.

Other Primary Batteries. Many other electrochemical systems have been used as primary batteries to obtain special performance characteristics. The more prominent ones are listed in Table 11-14.

**FIGURE 11-52** Construction of solid electrolyte cells: (a) silver iodide cell; (b) lithium iodide cell.

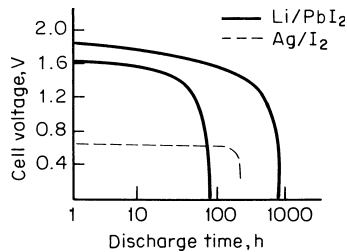


FIGURE 11-53 Typical discharge curves of solid dielectric electrolyte cells.

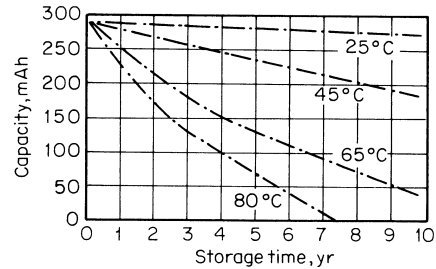


FIGURE 11-54 Capacity retention vs. temperature of solid electrolyte cells. (Sigma Technologies International, Inc.)

Recharging Primary Batteries. Recharging primary batteries is a practice that should generally be avoided since the cells are not designed for such use. In most instances it is impractical, and it could be hazardous in cells that are tightly sealed and not vented to permit the release of gases that form during charge and discharge. Most primary cells and batteries are labeled with a cautionary notice advising that they should not be recharged.

TABLE 11-14 Major Characteristics and Applications of Secondary Batteries

System	Characteristics	Applications
Lead-acid		
Automotive	Popular, low-cost secondary battery—moderate capacity, high-rate and low-temperature performance	Automobile starting, lighting, ignition (SLI); lawnmowers, tractors, marine, float service
Motive power	Designed for deep 6- to 9-h discharge, cycling service	Industrial trucks, materials handling; special types used for submarine power
Stationary	Designed for standby float service, long stand life	Emergency power—uninterruptible power supplies
Valve-regulated	Low maintenance, moderate cost, good float capability moderate cycle life	Many of the above applications, plus, TV, portable tools, lights and appliances, radios and cassettes and tape players
Nickel-cadmium		
Vented	Good high-rate, low-temperature capability; flat voltage, excellent cycle life	Aircraft batteries, industrial and emergency-power applications, communication equipment
Valve-regulated	Good high-rate, low-temperature performance, excellent cycle life, low maintenance	Photography, portable tools, appliances, standby power
Lithium-ion	Good gravimetric and volumetric energy and power, high cell voltage	Consumer electronics
Nickel-metal hydride	Replacement for nickel-cadmium, slightly higher cost, less robust low-temperature performance	Same as nickel-cadmium
Zinc-silver oxide	High energy density, good high-rate capability, low cycle life	Lightweight portable radio, TV, and communication equipment; torpedo propulsion, drones, submarines, and other military applications

Some Leclanche zinc-carbon cells can be recharged for several cycles under carefully controlled conditions. For successful recharging, the cell should be placed on charge soon after removal from discharge and at a low rate (about 16 h charge time). The cell voltage on discharge should not be less than 1.0 V when it is removed for charging. The cells must be returned to service soon after recharging, since the shelf life after recharge is poor. Note the recent introduction of Rayovac Renewal "reusable alkaline batteries."

11.8.3 Secondary Batteries

General. Secondary (rechargeable) batteries are widely used in many applications. Most are characterized, in addition to their ability to be recharged, by high power densities, by their capability to be discharged at high rates, by flat discharge curves, and by good low-temperature performance. Their energy densities are usually lower than those of primary batteries. The characteristics of some secondary batteries are listed in Table 11-14.

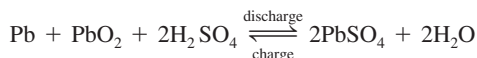
The applications of secondary batteries fall into two major categories:

1. Those applications where the secondary battery is used essentially as a primary battery, but recharged after use. Secondary batteries are used in this manner for convenience (as in handheld calculators or electronic flash units), for cost savings (as they can be recharged rather than replaced), or for power drains beyond the level of primary batteries.
2. Those applications where the secondary battery is used as an energy-storage device, being charged by a prime energy source and delivering its energy to the load on demand. Examples are automotive and aircraft systems, and emergency and standby power sources.

A summary of some of the major applications of the various types of secondary batteries is given in Table 11-14.

Lead-Acid Battery ($Pb-PbO_2$). The lead-acid battery is the most widely used secondary battery. Its low cost, reliability, and generally favorable performance characteristics account for its acceptance in many different applications. This type of battery is manufactured in many sizes, ranging in capacity from less than 1 Ah (small plastic-encased or sealed portable cells) to several thousand amperehours for stationary and vehicle-propulsion types. Characteristics of typical cells are summarized in Table 11-14.

Composition. The lead-acid battery uses highly reactive sponge lead for the negative electrode, lead dioxide as the active positive material, and a sulfuric acid solution for the electrolyte. As the cell discharges, the active materials of both electrodes are converted into lead sulfate. The sulfuric acid electrolyte also takes part in the reaction producing water. On charge, the reverse reactions take place. The state of charge of the battery can be determined in some cases by measuring the specific gravity of the electrolyte, which decreases on discharge and increases on charge. The discharge and charge reactions of the battery are



At the end of charge, electrolysis of water may occur, producing hydrogen at the negative and oxygen at the positive electrode.

Construction. The most common construction for the lead-acid cell is the pasted-plate design. A cross section of an automotive-type battery using this construction is shown in Fig. 11-55. The active material for each electrode is prepared as a paste by mixing finely divided lead oxides and suitable expander materials with sulfuric acid. The paste is spread onto a lead-alloy grid which provides the necessary electrical conductivity and structure to hold the active materials. The resulting plates are soldered or welded to connecting straps to form positive and negative plate groups which are interleaved. Separators are placed between the electrodes, and the completed element is

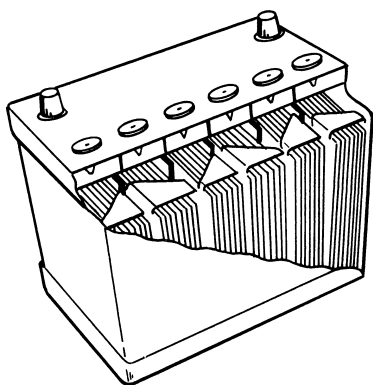


FIGURE 11-55 Cross section of lead-zinc automotive battery. (GNB, Inc.)

placed in a container. The container is designed with a sediment space under the element to safely collect any of the active material that is dislodged. Sufficient headroom is provided above the plates to hold excess electrolyte and allow electrode growth. Conventional lead-acid batteries often employ alloy-strengthened grids; calcium and antimony are the common alloying metals. The alloying is necessary to provide adequate strength for the thin grid structure to facilitate casting.

The low maintenance value regulated lead-acid batteries, which became popular in the mid-1970s, use calcium-lead grids, which are more resistant to corrosion and self-discharge. Water loss from gassing during charge is minimized in this design. The battery is filled with an excess of electrolyte and closed to prevent contamination. Other design features are improved separator materials which reduce the possibility of internal shorting, enclosed internal connectors, and lightweight, high-impact-strength polypropylene cases.

Other lead-acid batteries are similar in design to the automotive battery but vary in lead-alloy composition, plate thickness, separators, container, etc., to optimize the performance characteristics for the particular application.

General Performance Characteristics. The general performance characteristics of the lead-acid battery are given in Fig. 11-56.

Voltage. The nominal voltage of the lead-acid cell is 2 V; the voltage on open circuit is a direct function of the specific gravity, ranging from 2.12 V for a cell with 1.28 specific gravity to 2.05 V at 1.21. Figure 11-57 presents typical discharge curves for the lead-acid cell. The end of discharge cutoff voltage is usually about 1.75 V per cell but can be as low as 1.0 V per cell at extremely high rates, as in automotive starting service.

Specific Gravity. The selection of the specific gravity of the electrolyte at the start of discharge depends on the service requirements. The electrolyte concentration must be high enough for good electrical conductivity and to fulfill electrochemical requirements, but not so high as to cause separator deterioration or corrosion of other parts of the cell, which would shorten life and increase self-discharge. A specific gravity of 1.26 to 1.28 is usually used in automotive and high-performance batteries, and one as low as 1.21 for stationary standby batteries. The specific gravity should be reduced in high-temperature climates.

During discharge (Fig. 11-57), the specific gravity decreases about 0.125 to 0.150 points from a fully charged to a fully discharged condition. The change is proportional to the ampere-hours discharged. The specific gravity is thus an excellent means for checking the state of charge in a flooded battery. One must wait 5 or 10 min after discharging prior to measurement of specific gravity to allow the acid concentration to equilibrate. On charge, the change in specific gravity should similarly be proportional to the ampere-hour charge accepted by the cell, but there is a lag because complete mixing of the electrolyte does not occur until gassing commences near the end of the charge.

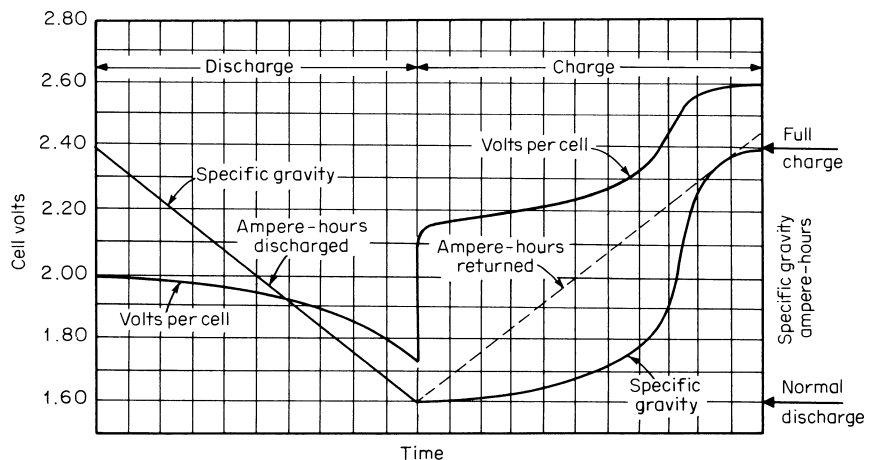


FIGURE 11-56 Performance characteristics of lead-acid cells. (GNB, Inc.)

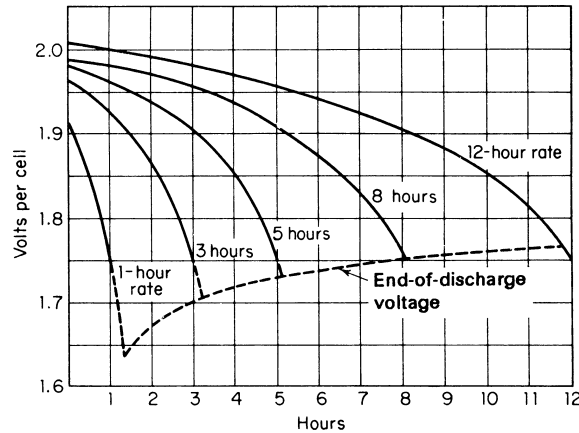


FIGURE 11-57 Discharge curves of lead-acid cells at different hour rates.

Service Life. The service life of a typical automotive-type lead-acid cell is shown in Fig. 11-58 for different discharge rates and temperatures. These curves have been normalized to the 20-h rate at 25°C. A 100-Ah cell, for example, will deliver 20 h of service when discharged at 5 A at 25°C or 1 h of service when discharged at -40°C at 20 A. Typically, higher service capacity is obtained at lower discharge rates and higher temperatures. In general, a battery may be discharged without harm at any rate of current it will deliver, but the discharge should not be continued beyond the point where the cell approaches exhaustion or where the voltage falls below a useful value.

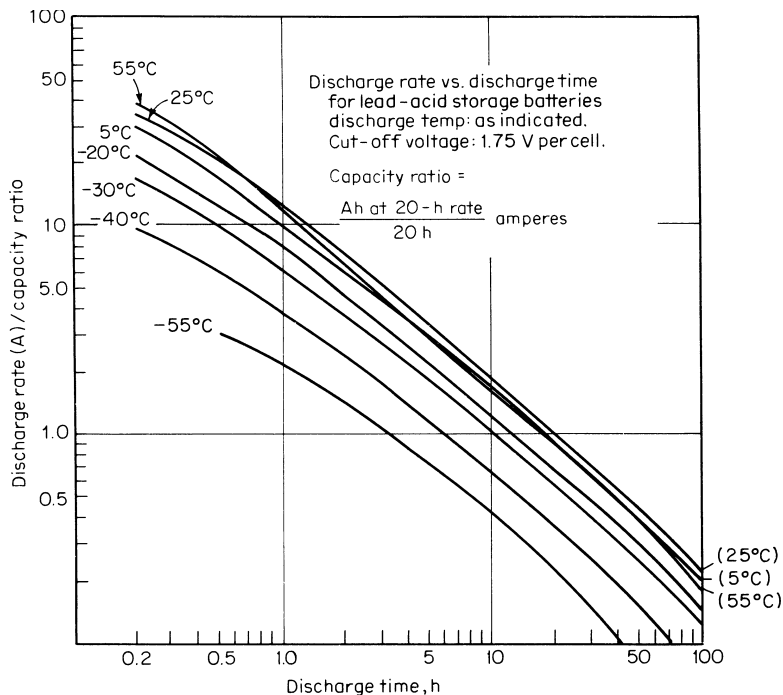


FIGURE 11-58 Service-capacity curves of lead-acid batteries.

Automotive cells are typically made with thinner plates, have a larger surface area, and use a higher concentration of electrolyte than motive-power and stationary batteries, so higher currents can be drawn at higher voltage levels. Hence, the electrical output of stationary batteries, which are designed for long-life service, will be somewhat lower to that indicated in Fig. 11-58.

Temperature. The variation of the performance of the lead-acid cell at different temperatures and loads is given in another form in Fig. 11-59. Although the battery will operate over a wide temperature range, continuous operation at high temperatures may reduce cycle life as a result of the increase in the rate of corrosion.

Self-Discharge. The self-discharge rate (loss of battery capacity during storage) depends on a number of factors, including the type of lead alloy used, the concentration of electrolyte, the age of the battery, and temperature. Self-discharge is caused by local chemical reactions between components of the plate and occurs almost entirely in the negative electrode. The rate of self-discharge is about 15% per month for antimonial-lead batteries at 25°C. Batteries using purer lead grids have substantially lower rates of self-discharge. Capacity lost by self-discharge can be recovered by recharging the battery. For best practice, a battery on stand should be recharged every 3 to 6 months, since prolonged storage and self-discharge can cause irreversible damage and make recharge difficult, owing to sulfation of the plates.

Lead-Calcium Cells. The lead-calcium cell uses a small percentage of calcium to give the lead grid the necessary physical rigidity in place of a larger amount of antimony normally used. Thus, it is closer to a pure-lead grid and has considerably reduced self-discharge due to local chemical action. The calcium alloy cells are best suited for standby float or open-circuit service rather than a cycling type of use. Frequent recharging in cycle use causes the grid in the positive plate to enlarge owing to corrosion of the lead grid and shortens life expectancy. Because of the improved performance, in terms of self-discharge and life, the use of calcium has largely replaced the use of antimony in the storage-battery market.

Nickel-Cadmium Batteries. The major alkaline secondary battery is the nickel-cadmium battery, which is noted for high power capability, long cycle life, good low-temperature performance, ruggedness, and reliability. This battery system is manufactured in many sizes, ranging from the small sealed button and

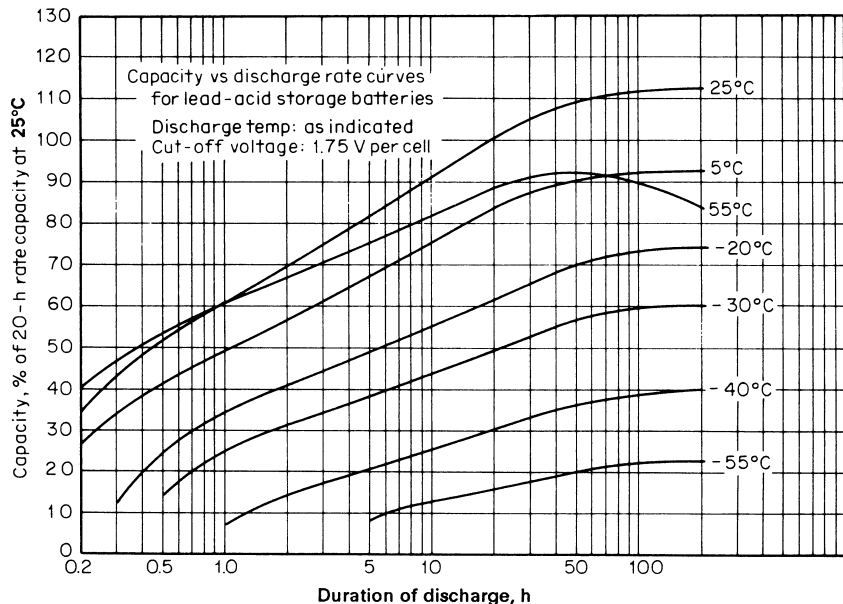


FIGURE 11-59 Performance of lead-acid batteries at various temperatures.

cylindrical cells with capacities as low as 0.020 Ah to larger vented cells for stand by and emergency service with capacities over 1,000 Ah. The nominal voltage of the nickel-cadmium cells is 1.2 V; the open-circuit voltage is 1.4 V. Table 11-14 lists the characteristics of different types of nickel cadmium cells.

Nickel-Metal Hydride. The nickel-metal hydride battery technology has become widely used in the last 10 years for consumer electronics as well as in propulsion and industrial applications. This technology is replacing nickel-cadmium batteries in many applications due to the environmental concerns

related to cadmium. Nickel-metal hydride cells use the same nickel electrode as does the nickel-cadmium battery, but the negative electrode consists of hydrogen (generated during charge) absorbed in a metal alloy. This electrochemical couple is well-known in a related technology, nickel-hydrogen batteries, which are used in high value satellite applications. The cost of the metal hydride battery is more than for nickel-cadmium, but still competitive for consumer and industrial products. It also exhibits more capacity per unit mass than does nickel-cadmium, but generally has lower discharge rate capability.

Construction of a typical cylindrical nickel-metal hydride cell for consumer products is shown in Fig. 11-60. The cell contains a safety vent, but is normally sealed to retain the hydrogen that is generated during charge. Cells are also available in button and prismatic configurations. Large, industrial scale cells are also available, and an example is shown in Fig. 11-61.

Typical voltage performance curves for a cylindrical cell are shown in Fig. 11-62. The technology has discharge limitations below about -20°C , but performs reasonably above that temperature. It does exhibit the

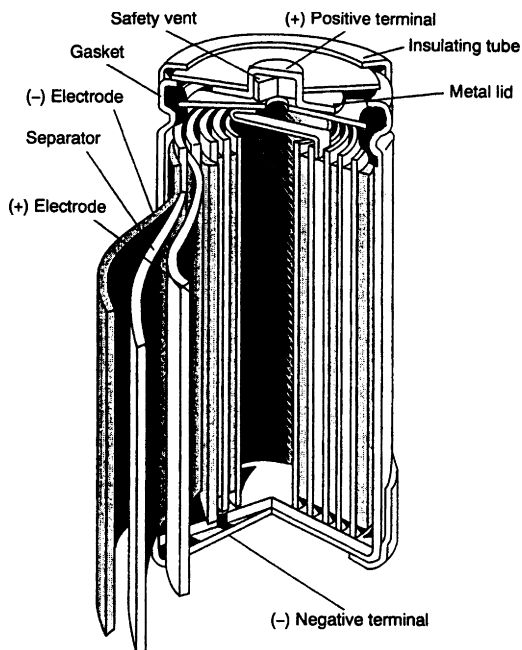


FIGURE 11-60 Construction of a sealed cylindrical nickel-metal hydride battery. (Courtesy of Duracell Inc.)

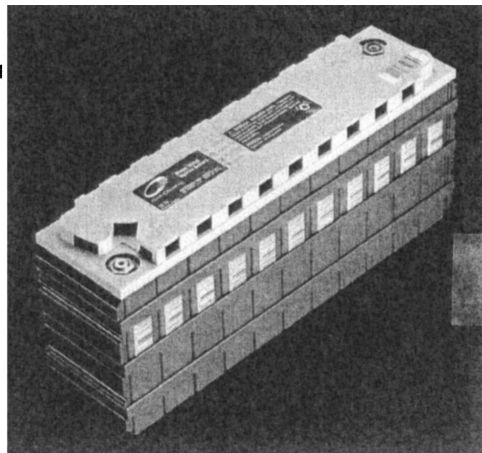
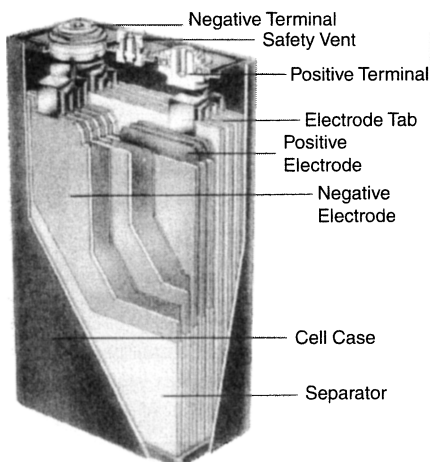
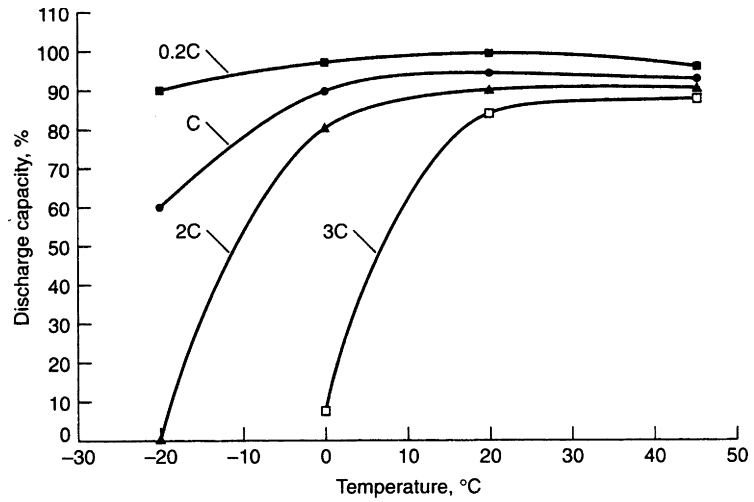
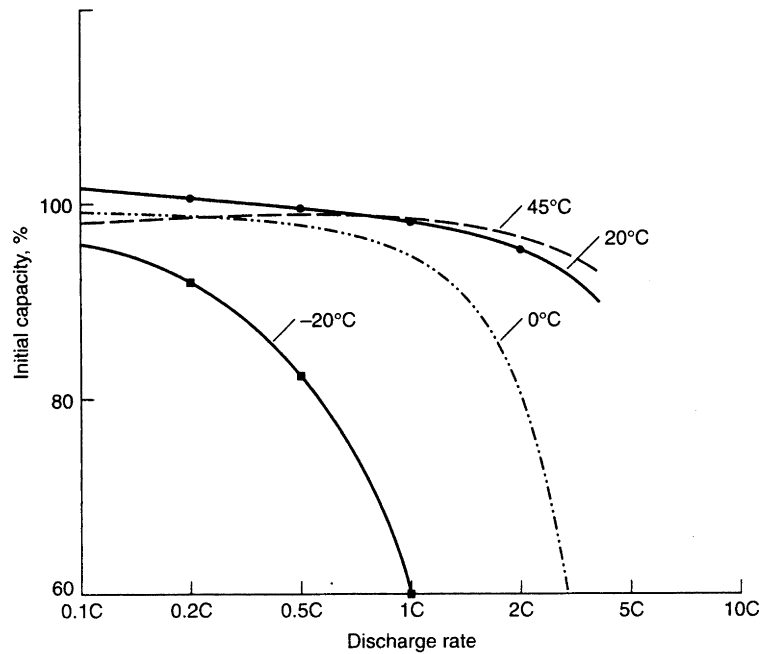


FIGURE 11-61 GM Ovonic 90-Ah prismatic cell and 13-V module.



(a)



(b)

FIGURE 11-62 (a) Discharge capacity vs. ambient temperature for sealed cylindrical nickel-metal hydride batteries at various discharge rates; end voltage 1.0 V/cell. (b) Discharge capacity (% of 0.2C rate) vs. discharge rate (C-rate) for sealed cylindrical nickel-metal hydride batteries at various temperatures; end voltage 1.0 V/cell.

memory effect, similar to nickel-cadmium cells, and this must be accommodated during use of the battery. However, there are several active research and development programs on the nickel-metal hydride technology, and improvements in performance and packaging are ongoing.

Rechargeable Ambient-Temperature Lithium Batteries. A huge range of new battery chemistries and products has become available in the last 5 to 10 years based on lithium. These batteries typically operate at close to room temperature, and provide significant advantages in gravimetric and volumetric energy and power characteristics relative to other rechargeable batteries. Products are available in an almost limitless range of electrochemistries and materials, and are known as lithium-ion, lithium polymer, lithium alloy, and lithium metal. The common material is lithium, but it may be present in metallic or ionic form, and there is a wide range of positive electrodes used, including cobalt oxide, manganese dioxide, and an equally wide range of electrolytes (e.g., organic liquids, gels, polymers), and conductive salts (e.g., lithium hexafluorophosphate). It is impossible to generalize when describing this technology, but rather specific types and products must be considered. However, various versions of this technology are being used by the millions of units in many consumer electronics products, and they are being evaluated for larger industrial and propulsion applications.

Cell construction of a typical cylindrical lithium-ion cell is shown in Fig. 11-63. This technology is also available in prismatic and pouch cell designs. Cell capacities range from less than 1 Ah to over 150 Ah. A major advantage of the technology is the high operating voltage per cell, typically in the range of 2.5 to 4.2 V. This translates into fewer cells in series to achieve a given battery voltage. Typical performance data for small cylindrical cells as a function of discharge rate and temperature are shown in Fig. 11-64. Generally, the discharge power capability of this technology is not as good as that for nickel-cadmium batteries. These batteries are generally more expensive than commercial alternatives, but prices have been dropping as production capacity is increased.

It should be kept in mind that the use of rechargeable ambient-temperature lithium batteries must be carefully controlled to maintain battery safety. Many cells and battery packs include a controller which consists of electronics and software to carefully monitor, adjust, or terminate charge and discharge.

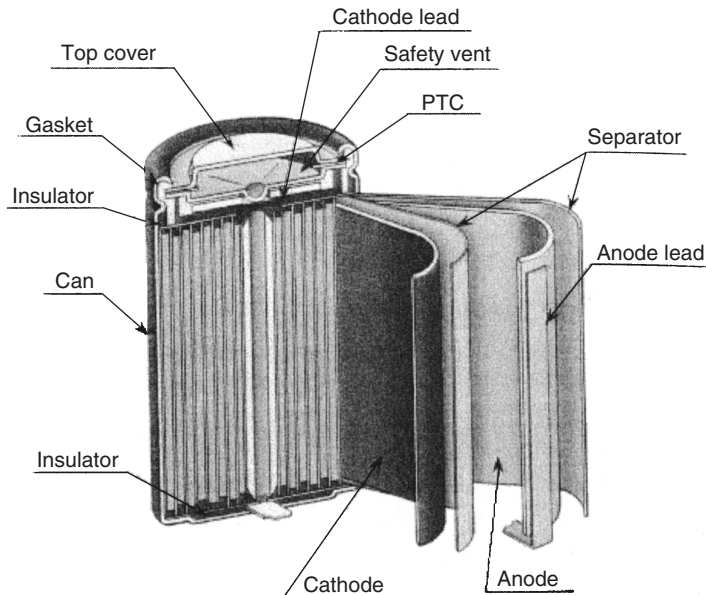


FIGURE 11-63 Cross-sectional view of a cylindrical Li-ion cell. (Courtesy of the University of South Carolina. Reproduced with permission from the *Journal of Power Sources*.)

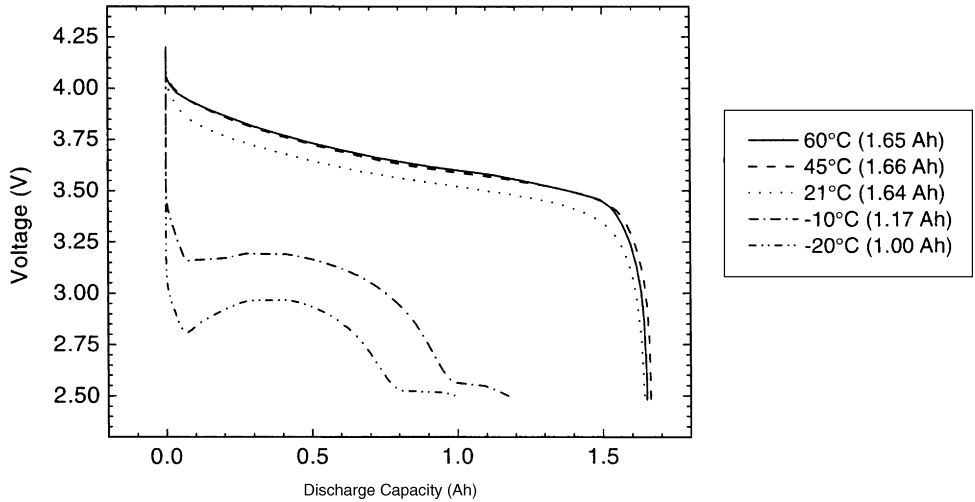


FIGURE 11-64 Approximate C-rate discharge of an 18650-type C/LiCoO₂ battery at various temperatures when charged in a CCCV regime at 1.65 A to 4.2 V for 2.5 hours, then discharged at 1.5 A. The average voltage at 21°C was 3.6 V, and at -20°C 2.9 V. (Courtesy of NEC Moli Energy.)

There have been numerous accidents involving this technology, and there are significant restrictions on transporting large quantities of cells and batteries on commercial aircraft, for example. This technology is also less tolerant to physical abuse than comparable battery chemistries, and care must be taken in harsh environments to avoid battery venting or thermal runaway.

The technology continues to evolve and improve in terms of performance and safety. There are many active research and development programs in progress worldwide to make products more robust, deliver higher discharge rates, and extend cycle life. Improvements in safety are also ongoing. This technology area is poised to continue growing for most small battery applications, and it may also become viable for large industrial and propulsion applications as further improvements in safety and control are realized.

The Battery Field. Readers are referred to an excellent in-depth technical review of batteries: *Modern Battery Technology*, Clive D. S. Tuck (ed.), West Sussex, England, Ellis Horwood Limited, ISBN 0-13-5902665-5. Another comprehensive battery reference is the *Handbook of Batteries*, 3rd ed., David Linden (ed.), New York, McGraw-Hill. This reference includes listings of companies that manufacturing various batteries.

The room-temperature solid electrolyte silver ion conducting devices described in association with Fig. 11-51 are available from Sigma Technologies International, Inc., Tucson, Arizona.

Several other advanced rechargeable battery technologies are being developed worldwide for many diverse applications. They are subject to government and industrial research and development, and the organizations and corporate sponsors/owners change frequently in this dynamic field. The following is a snapshot of the current advanced technologies in development.

- Lithium-alloy/iron sulfide high temperature batteries—Argonne National Laboratory
- Sodium/nickel chloride high temperature batteries (Zebra battery)—MES-DEA SA (Swiss), Beta Research and Development
- Sodium/sulfur high temperature batteries—NGK Insulator
- Vanadium-redox aqueous flowing electrolyte batteries—VRB Power Systems
- Zinc-air batteries—Electric Fuel Battery Corp
- Zinc/bromine flowing electrolyte batteries—ZBB Technologies

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Linden, D., and Reddy, T., *Handbook of Batteries*, 3rd ed., McGraw-Hill, New York, 2002.

11.9 FUEL CELLS

11.9.1 General Concepts

A *fuel cell* is an electrochemical device that continuously converts the chemical energy of a fuel (and oxidant) to electrical energy. The essential difference between a fuel cell and a battery is the continuous nature of the energy supply. The fuel and the oxidant, which is usually oxygen, are supplied continuously to a fuel cell from an external source.

The fuel cell uses liquid or gaseous fuels, such as hydrogen, hydrazine, hydrocarbons, and coal gas. The oxidant in a fuel cell is gaseous oxygen (or air). Fuel cells are close to receiving widespread commercial acceptance in stationary power generation due to improvements in efficiency and reductions in capital cost. Fuel cell-based generating stations typically have operating efficiencies ranging from 40% to 50%. In comparison, many generating stations operate at 30% to 35% efficiency.

A practical fuel cell power plant, depicted in Fig. 11-65, consists of at least three basic subsystems:

1. A power section, which consists of one or more fuel cell stacks—each stack containing many individual fuel cells usually connected in series to produce a stack output ranging from a few to several hundred volts (direct current). This section converts processed fuel and the oxidant into dc power.
2. A fuel subsystem that manages the fuel supply to the power section. This subsystem can range from simple flow controls to a complex fuel-processing facility. This subsystem processes fuel to the type required for use in the fuel cell (power section).
3. A power conditioner that converts the output from the power section to the type of power and quality required by the application. This subsystem could range from a simple voltage control to a sophisticated device that would convert the dc power to an ac power output.

In addition, a fuel cell power plant, depending on size, type, and sophistication, may require an oxidant subsystem as well as thermal and fluid management subsystems.

11.9.2 Operation of Fuel Cells

A simple fuel cell is illustrated in Fig. 11-66. Two catalyzed carbon electrodes are immersed in an electrolyte (acid in this illustration) and separated by a gas barrier. The fuel, in this case hydrogen, is bubbled across the surface of one electrode while the oxidant, in this case oxygen from ambient

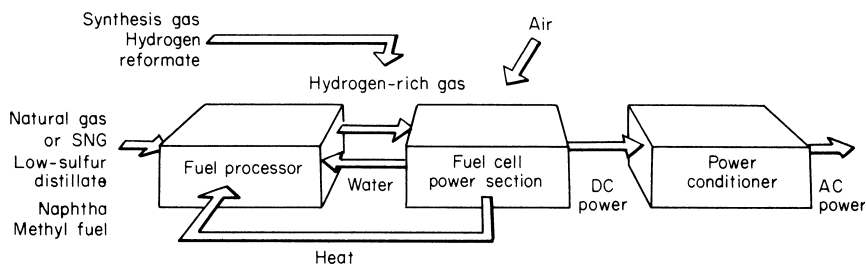


FIGURE 11-65 Generalized schematic diagram of a fuel cell power plant.

air, is bubbled across the other electrode. When the electrodes are electrically connected through an external load, the following events occur:

1. The hydrogen dissociates on the catalytic surface of the fuel electrode, forming hydrogen ions and electrons.
2. The hydrogen ions migrate through the electrolyte (and a gas barrier) to the catalytic surface of the oxygen electrode.
3. Simultaneously, the electrons move through the external circuit to the same catalytic surface.
4. The oxygen, hydrogen ions, and electrons combine on the oxygen electrode's catalytic surface to form water.

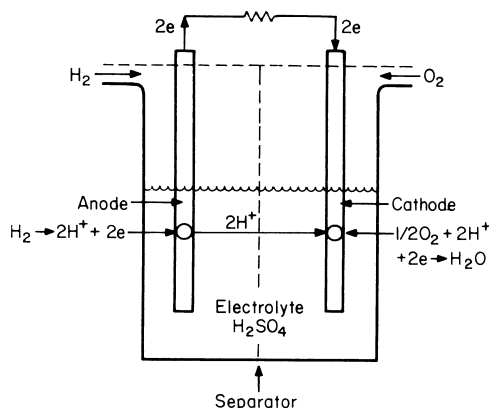


FIGURE 11-66 Operation (reaction mechanism) of the fuel cell.

The reaction mechanisms of this fuel cell, in acid and alkaline electrolytes, are shown in Table 11-15. The major differences, electrochemically, are that the ionic conductor in the acid electrolyte is the hydrogen ion (or, more correctly, the hydronium ion, H_3O^+) and the OH^- or hydroxyl ion in the alkaline electrolyte. Further, in the acid electrolyte the product, water, is produced as the cathode and in the alkaline electrolyte fuel cell at the anode.

The net reaction is that of hydrogen and oxygen producing water and electrical energy. As in the case of batteries, the reaction of one electrochemical equivalent of fuel theoretically will produce 26.8 Ah of dc electricity at a voltage that is a function of the free energy of fuel-oxidant reactions. At ambient conditions, this potential is ideally 1.23 V dc for a hydrogen-oxygen fuel cell.

11.9.3 Major Components of the Fuel Cell

The important components of the individual fuel cell are

1. The *anode* (fuel electrode) must provide a common interface for the fuel and electrolyte, catalyze the fuel oxidation reaction, and conduct electrons from the reaction site to the external circuit (or to a current collector that, in turn, conducts the electrons to the external circuit).
2. The *cathode* (oxygen electrode) must provide a common interface for the oxygen and the electrolyte, catalyze the oxygen reduction reaction, and conduct electrons from the external circuit to the oxygen electrode reaction site.
3. The *electrolyte* must transport one of the ionic species involved in the fuel and oxygen electrode reactions while preventing the conduction of electrons (electron conduction in the electrolyte causes a short circuit). In addition, in practical cells, the role of gas separation is usually provided by the electrolyte system. This is often accomplished by retaining the electrolyte in the pores of a matrix (or inert blotter). The capillary forces of the electrolyte within the pores allow the matrix to separate the gases, even under some pressure differential.

TABLE 11-15 Reaction Mechanisms of the H_2 - O_2 Fuel Cell

	Acid electrolyte	Alkaline electrolyte
Anode	$\text{H}_2 \rightarrow 2\text{H}^+ + 2e^-$	$\text{H}_2 + 2\text{OH}^- \rightarrow 2\text{H}_2\text{O} + 2e^-$
Cathode	$\frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2e^- \rightarrow \text{H}_2\text{O}$	$\frac{1}{2}\text{O}_2 + 2e^- + \text{H}_2\text{O} \rightarrow 2\text{OH}^-$
Overall	$\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$	$\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$

Other components also may be necessary to seal the cell, to provide for gas compartments, and to separate one cell from the next in a fuel cell stack.

11.9.4 General Performance Characteristics

The performance of a fuel cell is represented by the current density versus voltage (or polarization) curve (Fig. 11-67). Whereas ideally a single $\text{H}_2\text{-O}_2$ fuel cell could produce 1.23 V dc at ambient conditions, in practice, fuel cells produce useful voltage outputs that are somewhat less than the ideal and decrease with increasing load (current density). The losses or reductions in voltage from the ideal are referred to as *polarization*, as illustrated in Fig. 11-67.

These losses include the following:

1. Activation polarization represents energy losses that are associated with the electrode reactions.
2. Ohmic polarization represents the summation of all the ohmic losses within the cell, including electronic impedances through electrodes, contacts, and current collectors and ionic impedance through the electrolyte. These losses follow Ohm's law.
3. Concentration polarization represents the energy losses associated with mass transport effects. For instance, the performance of an electrode reaction may be inhibited by the inability of reactants to diffuse to or products to diffuse away from the reaction site.

The net result of these polarizations is that practical fuel cells produce between 0.5 and 0.9 V dc at currents of 100 to 400 mA/cm² of cell area. Fuel cell performances can be increased by increasing cell temperature and reactant partial pressure. For any fuel cell, the tradeoff always exists between achieving higher performance by operating at higher temperature or pressure and confronting the materials and hardware problems imposed at the more severe conditions.

11.9.5 Fuel Cell Systems

Classification and Types. Fuel cell systems can take a number of different configurations, depending on the combination of type of fuel and oxidant, whether the fueling is direct or indirect, the type

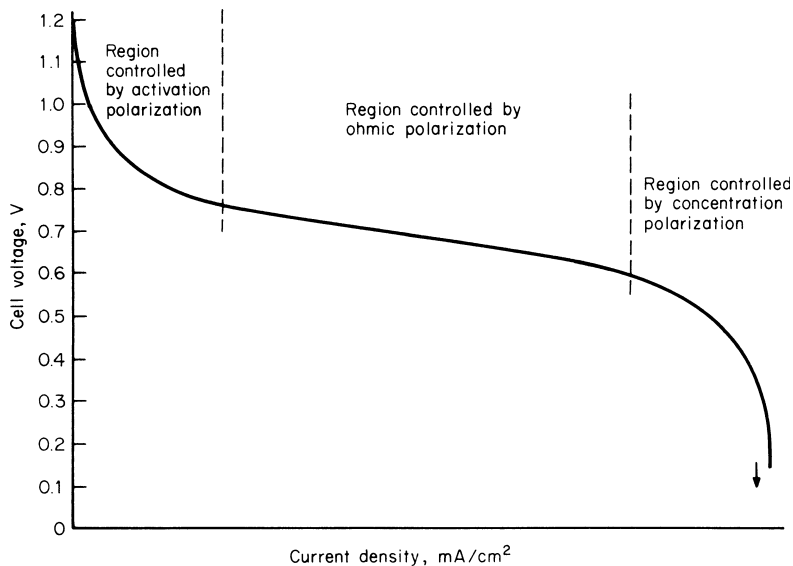


FIGURE 11-67 Fuel cell polarization curve.

of electrolyte, the temperature of operation, etc., although in actual practice, the number of combinations is limited. A listing of the practical fuel cell systems is given in Table 11-16.

Acid Fuel Cells. Table 11-16 lists two types of acid fuel cells (solid polymer electrolyte and phosphoric acid), aqueous alkaline fuel cells, molten carbonate fuel cells, and solid oxide fuel cells. Acid fuel cells are characterized by the following:

Ionic conduction is provided by hydrogen ions [or by hydronium ions (H_3O^+)].

Platinum or platinum alloys (in very small quantity) are the active electrocatalysts.

Carbon (graphite) is an acceptable material of construction for current collectors, gas separators, etc., and is commonly used.

Solid Polymer Electrolyte System. The solid polymer electrolyte (SPE) system uses an ion-exchange membrane as the electrolyte. The advantages of the SPE fuel cell are (1) the electrolyte, being a solid, cannot change, move about, or vaporize from the system; and (2) the only liquid in the fuel cell is water, minimizing corrosion. The disadvantages are (1) the SPE must be hydrated (water-saturated) to perform; consequently, operation must be under conditions where the by-product water does not vaporize into the reaction air stream faster than it is produced; this constrains cell operation to under 60°C at ambient pressure and about 120°C at elevated pressures; and (2) the SPE freezes at about 0°C and undergoes a freeze-drying phenomenon. This constraint is applicable to those where low-temperature capability is not a requirement.

Due to their inability to operate much above 120°C , SPE fuel cells are best suited for use with hydrogen-rich gases that contain little or no carbon monoxide. Carbon monoxide inhibits the fuel cell anode reaction, the degree of inhibition decreasing with increasing temperature. Consequently, SPE fuel cells have found their important applications in the space program operating on pure hydrogen or in military applications operating on hydrogen obtained by the decomposition of a hydride.

TABLE 11-16 Classification of Practical Fuel Cells

Application	Fuel	Oxidant	Electrolyte	Temperature
Remote				
Space	Direct H_2	Liquid O_2	Aqueous alkaline	Low, intermediate
			Solid polymer	Low
Undersea	Direct H_2	Liquid O_2	Aqueous alkaline	Low
	Direct hydrazine	Hydrogen peroxide		
Military				
Low power, ≤ 100 W	Indirect hydride	Air	Aqueous alkaline	Low
			Solid polymer	
High power, ≥ 500 W	Indirect hydrocarbon	Air	Phosphoric acid	Intermediate
	Indirect methanol			
Commercial power				
Dispersed (or on-site)	Indirect hydrocarbon		Phosphoric acid	Intermediate
	Indirect methanol, ethanol	Air	Molten carbonate	High
	Direct coal gas			
Central station	Indirect coal	Air	Phosphoric acid	Intermediate
	Direct coal gas		Molten carbonate	High
			Solid oxide	Very high
Vehicle	Hydrogen			
	Hydride	Air	Phosphoric acid	Intermediate
	Indirect methanol			
	Indirect hydrocarbon			

Phosphoric Acid Electrolyte System. The phosphoric acid electrolyte system operates at 150 to 220°C. At lower temperatures, phosphoric acid is a poor ionic conductor. At higher temperatures, material stability (carbon and platinum) becomes limiting. The advantages of phosphoric acid fuel cells are (1) the electrolyte is very stable, (2) the phosphoric acid can be highly concentrated (~ 100%) where the water vapor pressure is very low and steady-state water removal by the reactant gases will always equal product water rate, and (3) at 150 to 220°C, the anode performance is very good even on fuels containing up to 5% carbon monoxide. The disadvantage of phosphoric acid fuel cells is that the cathode performance is sluggish. In fact, the major technology thrusts in phosphoric acid are toward improvement of the cathode. The phosphoric acid fuel cell is a preferred system for use with fuels containing carbon oxides.

Alkaline Fuel Cells. Although early alkaline fuel cells operated at relatively high temperature (~250°C) with concentrated (85 wt%) potassium hydroxide, systems developed more recently operate at much lower temperatures (<120°C) using less concentrated (35 to 50 wt%) potassium hydroxide. The lower temperature enables the use of matrices to retain the electrolyte and increases the life of other components.

Alkaline fuel cells are characterized by the following:

Ionic conduction is provided by hydroxyl (OH⁻) ions.

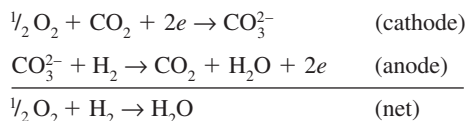
A wide range of electrocatalysts can be used, including nickel, silver, metal oxides, spinels, and noble metals—although the truly high-performance systems use at least small amounts of noble metal.

Construction materials include carbon, nickel, and stainless steel.

The advantages of alkaline fuel cells are that (1) cathode performance is much better than for acid fuel cells and (2) materials of construction tend to be low in cost. The primary disadvantage is that the electrolyte reacts with carbon oxides to form potassium carbonate. This severely limits the cells' performance. Thus, alkaline fuel cells have only limited application where carbonaceous fuels or air is used as a reactant. The important applications (space and underseas) involve pure hydrogen and oxygen.

Molten Carbonate Fuel Cells. Molten carbonate fuel cells use an alkali metal (Li, K, Na) carbonate as the electrolyte. Since these salts can function as electrolytes only when in the liquid phase, the cells operate at 600 to 700°C, which is above the melting points of the respective carbonates. Molten carbonate cells are characterized by the following:

Ionic conduction is by the carbonate ion; thus, the carbonate ion must be involved in the two electrode reactions:

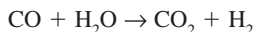


A consequence of this is that CO₂ must be recycled from the anode to the cathode.

At 600 to 700°C, electrode reactions proceed without highly specific catalysts. Nickel and nickel oxide work quite well; noble metals are not used.

Construction materials include nickel and ceramics.

The advantages of molten carbonate fuel cells are that (1) cell performance is good, activation polarization is small; (2) at 600 to 700°C, any carbon monoxide in the fuel converts to hydrogen on the anode via the water gas shift reaction, that is,



(as a result, fuel gases high in carbon monoxide are readily used); and (3) waste heat from the fuel cell can be available at a relatively high temperature ($>500^{\circ}\text{C}$), enabling its use in bottoming or industrial heating cycles.

Disadvantages are that (1) the high temperature imposes severe constraints on materials suitable for long lifetimes and (2) a course of carbon dioxide is required to complete the cathode reaction (this is provided by recycling CO_2 from the anode exhaust to the cathode inlet). As a result, molten carbonate fuel cells are best suited for applications that integrate the fuel cell with a carbonaceous fuel processor, that is, a reformer or coal gasifier.

Solid Oxide Fuel Cells. As the name implies, solid oxide fuel cells employ a solid, nonporous metal oxide electrolyte, which allows ionic conductivity by the migration of oxide ions through the lattice of the crystal. Stabilized zirconia is commonly used as the electrolyte. The cells operate at 900 to $1,000^{\circ}\text{C}$. Whereas practical cells of the technologies previously discussed are normally packaged into “filter press” or “plate and frame” stack assemblies, solid oxide fuel cells are configured into tubular cell stacks.

Characteristics of the solid oxide fuel cell include the following:

Ionic conduction is provided by oxide ions.

The cathode employs metal oxides, such as praseodymium oxide or indium oxide; the anode uses nickel or nickel cermet.

Because of the high temperature, materials of construction will likely be confined to ceramics or metal oxides.

Solid oxide fuel cells offer advantages similar to those of molten carbonate cells, that is, good performance on fuels containing hydrogen or hydrogen and carbon monoxide, the elimination of noble-metal catalysts, and the availability of high-grade reject heat. In addition, they do not suffer the constraint of molten carbonate cells which require a carbon dioxide recycle to the cathode. The primary disadvantages are the very high temperature of operation and the severe material constraints imposed by the $\sim 1,000^{\circ}\text{C}$ temperature.

11.9.6 Low-Power Fuel Cell Systems

The advantageous characteristics of fuel cells led to the development of a number of different systems ranging in size from the portable units, 5 W or smaller to kilowatt power levels (where ease of operation, low maintenance, and silence are important), to large stationary plants delivering megawatts of power (where the high efficiency over the range from full to partial load and reduced pollution are significant). The lower-power fuel cells were designed mainly for military or special applications such as the space program. For the space applications and for forward-area military use, the fuel cell offers high energy densities that exceed the performance of batteries when operated over long periods of time.

Portable Fuel Cells. Fuel cells in the power range of up to about 200 W can be an attractive alternative to batteries for long-term operation, with potential reduction in the weight and cost. The size limitation of these portable fuel cell systems is generally too small to permit the use of elaborate fuel conditioning. Hence, easily handled and readily oxidized fuels (e.g., liquid or gaseous fuels such as hydrazine, methanol, and ammonia) and fuels that provide hydrogen through a simple physical or chemical reaction have been used in most fuel cell systems of this size and type. For these ground applications, air-breathing, rather than pure oxygen, systems are used.

While the fuel cell systems in this size and power range potentially have advantageous characteristics, system complexities and the development of new battery systems with higher energy densities have limited the interest and successful use of the low-power fuel cell.

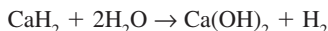
Direct Fuel Cell Systems. Direct-type fuel cells, in which the fuel can be introduced into the fuel cell without requiring conversion to hydrogen, were considered for small fuel cell systems because

they eliminated the need for a fuel-conditioning unit, thus saving important space and weight. Methanol (CH_3OH) and hydrazine (N_2H_4) were the main liquid fuels used. Methanol is directly oxidizable, but removal of the carbonate, one of the reaction products of the dissolved methanol fuel cell in alkaline electrolytes, from the electrolyte is extremely difficult. Efforts then shifted to hydrazine. Hydrazine decomposes easily into hydrogen and nitrogen at the electrode surface; in fact, the voltage observed is that of hydrogen.

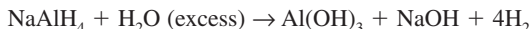
Major effort was directed toward a silent power source for forward-area military use. A 60-W, 24-V hydrazine-air fuel cell was developed in a configuration similar to the one used later for the metal hydride cell. The fuel cell used a 35% potassium hydroxide electrolyte and a 64% hydrazine monohydrate fuel and operated between 55 and 70°C with a fuel utilization of 600 Wh/kg. A larger 300-W, 24-V power source also was developed for forward-area use. This system weighed 20 kg, with electrolyte and 4 L of fuel and had a volume of 35 dm³. The fuel was sufficient for 12 h of operation at 300 W. Field tests confirmed the successful electrochemical functioning of the cell, but mechanical deficiencies caused early failure of the system.

Metal Hydride Fuel Cells. The majority of current portable fuel cell developments use a metal hydride as the source of hydrogen fuel. Metal hydrides are attractive because they can store large amounts of hydrogen more conveniently and with a higher energy density (total equivalents of hydrogen per total weight of hydrogen source and container) than hydrogen in a pressurized or liquefied form.

One type of metal hydride produces hydrogen by the reaction with water, for example, calcium hydride (CaH_2):

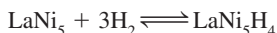


A second type of metal hydride, a reversible hydride, is based on the principle that certain metals or alloys (e.g., iron titanium, lanthanum nickel, and various other rare-earth metal and nickel alloys) have the ability to take up large amounts of hydrogen gas within their crystal structure. A reduction in pressure or an increase in temperature release the hydrogen. These hydrides can deliver hydrogen at about 500 Wh/kg.



The hydride, in the form of a solid pellet, delivers in excess of 2000 Wh/kg. Hydrogen for 4 h of operation is supplied to the fuel cell with a single 120-g charge. The Kipp generator delivers hydrogen to the fuel cell on demand; when no hydrogen demand exists, the pressure builds up in the generator, forcing water away from the fuel pellet and stopping the reaction.

A later design used a reversible metal hydride, lanthanum pentanickel hydride, as the source of hydrogen:



This change, replacing the exothermic sodium aluminum hydride generator with the reversible metal hydride source, which absorbs heat on the release of hydrogen, could reduce the total heat output of the system by 65%. The system was found to operate satisfactorily at 20°C, but higher ambient temperatures still caused problems because of the much higher operating temperature of the fuel cell stack.

SPE Fuel Cell. There is renewed interest in the SPE fuel cell for applications in which mobility is important and power requirements are low. The advantages of the SPE cell are ease of product water removal, simple construction, stable electrode-electrolyte interface, and favorable life characteristics.

The SPE cell is being considered for power levels from a few watts to 500 W, operating in the -40 to 50°C range with no restrictions on humidity. Special designs, including insulation for low temperatures and methods for waste heat disposal, probably will be required to achieve this performance. The cell operates on hydrogen and ambient air. Preferred fuel sources for hydrogen generation

TABLE 11-17 Utility Fuel Cell Power Plant Programs

Role	Size	Fuel	Efficiency, %	Electrolyte
On-site power plants	40–300 kW	Pipeline gas	39–42 or 90 (with reject-heat recovery)	Phosphoric acid
Dispersed (substation) power plants	5–25 MW	Petroleum- or coal-derived gas or liquid	41–47 or 80 (with reject-heat recovery)	Phosphoric acid
Central station power plants	150–600 MW	Coal	45–50	Molten carbonate or phosphoric acid

are magnesium and aluminum, which are reacted with salt water. Bottled hydrogen, hydride-stored hydrogen, or hydrides also may be used. With magnesium, it is expected to obtain energy densities (fuel consumption) of about 220 Wh/kg on a wet basis and 1300 Wh/kg on a dry basis. For longer missions, where a larger system weight can be tolerated, re-formed methanol combined with carbon monoxide absorption is being considered.

Utility Fuel Cell Power Plants. Interest in the fuel cell as a utility power plant results from its efficiency, its environmental acceptability, and its modular construction. The fuel cell may serve utilities in several ways, as summarized in Table 11-17. Relatively small fuel cell power plants (with a capacity ranging from 40 to 300 kW) could be set up in commercial and residential buildings. Such a plant would use natural gas as a fuel. The plant would provide both electric and thermal energy (the latter from the waste heat of the fuel cells), consuming the same amount of fuel ordinarily required for the thermal demand alone. Overall efficiencies approaching 90% have been projected for fuel cell power plants of this type. An advantage of the fuel cell is that the waste heat can be used without altering the power production characteristics. Larger plants, ranging in capacity from 5 to 25 MW, could be dispersed throughout an electric utility system to perform load-following duty efficiently, taking advantage of the higher efficiency of the fuel cell even at reduced loads. In the future, fuel cells could be integrated with coal gasifiers to provide large, central-station, base-load power plants that utilize coal directly. The capacity of such plants would range from 150 to 1,000 MW. A plant of this kind is projected to be more than 45% efficient, on the basis of the heating value of the coal consumed.

Phosphoric Acid Fuel Cells. The basic *cell structure* of the phosphoric acid fuel cell (PAFC) is shown in Fig. 11-68. It consists of

1. A *carbon or graphite separator-current collector plate* that separates hydrogen from the air of the adjacent cell (in a multicell stack) and also provides the electrical series connection between cells.
2. *Anode current collector ribs* that conduct the electrons from the anode to the separator plate. The ribbed configuration provides gas passages for hydrogen distribution to the anode.
3. An *anode* that consists of a porous graphitic substrate with the surface adjacent to the electrolyte treated with a platinum or platinum alloy catalyst.
4. An *electrolyte matrix* that retains the concentrated phosphoric acid.
5. A *cathode* that is similar to the anode but uses a modified noble-metal catalyst and an increased catalyst loading (usually 0.5 mg/cm²) to enhance the oxygen reduction kinetics.
6. *Cathode current collector ribs* that are also virtually identical to the anode ribs.

These single cells are stacked in series to produce the desired output power and voltage.

Phosphoric acid fuel cell power plants are also being considered for use in central stations. These power plants would utilize integrated coal gasifiers to supply the hydrogen-rich fuel and would provide base load power.

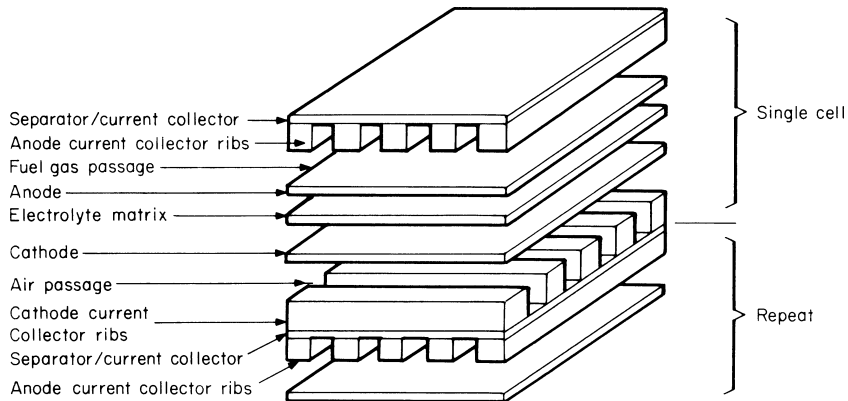


FIGURE 11-68 Basic phosphoric acid electrolyte fuel cell.

Molten Carbonate Fuel Cells. In contrast to the PAFC, molten carbon fuel cell (MCFC) development efforts are focused on large, multimegawatt (~600 MW) central-station power plants integrated with a coal gasifier. This focus is, in part, due to their high operating temperature and the problems inherent in starting (heating) and stopping (cooling) MCFC power plants.

Cell structure for the MCFC is geometrically very similar to that of the PAFC. The materials that are used, however, are very different from those used in the PAFC. The MCFC consists of

1. A *separator and current-collector plate* that separates the fuel gas from the air of the adjacent cell in a multicell stack and also provides the electrical connection between cells. Like its PAFC counterpart, it must be impermeable to hydrogen and oxygen, a good electronic conductor, and stable to fuel and air environments in the presence of 650°C carbonate salts.
2. An *anode current collector* that conducts the electrons from the anode to the separator plate. This current collector also must provide passage for fuel flow. In some configurations, this function is provided by ribbing or folding the separator plate.
3. An *anode* that consists of a porous nickel treated with a refractory oxide to reduce sintering. At the 650°C temperature, no other catalyst is required.
4. An *electrolyte system* comprising a mixture of lithium–potassium carbonate and inert powder (presently a lithium aluminate). This mixture forms a paste when molten and freezes to form a “tile” when cooled. This electrolyte system presents major challenges to MCFC development. It must have minimum ionic resistance while separating the fuel and oxidant gases at pressure differentials in excess of 0.07×10^5 Pa. In addition, it must be electronically insulating.
5. A *cathode* that is similar to the anode except that it uses nickel oxide (doped with lithium to impart electronic conductivity).
6. A *cathode current collector* that has similar requirements and configurational operations as the anode current collector. Since nickel is thermodynamically unstable, material options include lithium-doped nickel oxide and corrosion-resistant stainless steel.

As with the PAFC, individual cells are stacked in series to result in a cell stack of the required power and voltage output.

Molten Carbonate Fuel Cell Power Plants. The thrust of the MCFC program is the development of a central-station power plant, comprising a coal gasifier, gas cleanup system, MCFC

TABLE 11-18 Design Requirements and Goals for a Central Station MCFC Power Plant

Requirements	
Central station plant	
Power level	–675 MW(e)
Fuel specification	Illinois no. 6 coal
Modular construction	
Environmental	Projected 1985 federal requirements
Site characteristics	“Middletown” except for cooling tower heat rejection
Goals	
Base load duty with daily load following capability	
Heat rate	6.8×10^6 J/kWh
Capital installed cost (1982 dollars)	\$1500/kW(e)
Plant availability	85%
Life goals (75% capacity factor)	
Fuel cell stacks	6 years
Balance of plant	30 years
Startup/shutdown	
Startup: Cold startup in 4 to 6 h	
Shutdown: 100% to zero load in 3 h	
Daily load following	
Large-load-change response time of 2 h	
Small-load-change response rate up to 2%/min	
Abnormal conditions	
Complete-load rejection (breakers opening)	
Partial-load rejection (from power system breakup)	
Sustained abnormal voltage or frequency operation	
Limit fault current to 1.1 per unit current (rms basis)	
Other	
Independent var control	

(topping cycle), and gas or steam turbine (bottoming cycle). Design requirements and goals for a 675-MW power plant are described in Table 11-18. A possible power plant configuration would include

- 600 MCFC stacks (having five hundred 1-m² cells each) for a total 450-MW output
- 15 coal gasifiers capable of handling 3×10^{11} J/h each
- 10 heat-recovery steam generators
- Five 15-MW gas turbines
- One 150-MW steam turbine

Although the ultimate application of the MCFC will likely be as a large coal-fueled, central-station power plant, other applications such as that of dispersed or on-site generators with and without reject heat recovery are also being considered. Because of the high operating temperature, the quality of the MCFC's waste heat could be compatible with a variety of industrial heating applications. Also, at 600°C, in situ re-forming of methane or methanol is possible; this could result in a very efficient small power plant.

Direct Fuel Cell Systems. Methanol (CH₃OH) and hydrazine (N₂H₄) are the liquid fuels that have been used in direct fuel cells, since they are more readily oxidized than the fossil fuels. Work is still

in the development stage, and no systems were available commercially in the mid-1970s. Effort in recent years has been deemphasized.

Hydrazine has been used in a 60-W and larger configurations. The 60-W hydrazine unit is similar to the hydrogen fuel cell and delivers over 600 Wh/kg but was abandoned in favor of the hydrogen system. Similar experience was obtained with a larger 120-kg, 1.5-kW unit which degraded rapidly after 300 h of service.

A relatively small effort continues on direct hydrocarbon fuel cells, particularly with high-temperature (1,000 to 1,200°C) solid electrolyte fuel cells. The higher temperatures should allow direct reaction of the hydrocarbons with improved kinetics, although the potential benefits may be offset by the problems of high-temperature operation.

11.9.7 Fuel Cell Resources

Web sites

<http://www.fuelcells.org>

General Motors, <http://www.gm.com>

Fuel cell Today, <http://www.fuelcelltoday.com>

United Technologies, <http://www.utcpower.com>

11.10 MAGNETOHYDRODYNAMICS

By N.B. MORLEY and M.S. TILLACK

11.10.1 Introduction

The interaction of moving conducting fluids with electric and magnetic fields provides for a rich variety of phenomena associated with electro-fluid-mechanical energy conversion. Effects from such interactions can be observed in liquids, gases, two-phase mixtures, or plasmas. Numerous scientific and technical applications exist, such as heating and flow control in metals processing, power generation from conducting two-phase mixtures or conductor-seeded high-temperature gases, magnetic confinement of high-temperature plasmas—even dynamos that create magnetic fields in planetary bodies. Several terms have been applied to the broad field of electromagnetic effects in conducting fluids, such as *magneto-fluid-mechanics*, *magneto-gas-dynamics*, and the more common one used here—*magnetohydrodynamics*, or MHD.

Practical MHD devices have been in use since the early part of the twentieth century. For example, an MHD pump prototype was built as early as 1907.¹ More recently, MHD devices have been used for stirring, levitating, and otherwise controlling flows of liquid metals for metallurgical processing and other applications.^{2,3} Gas-phase MHD is probably best known in MHD power generation. Since 1959,^{4,5} major efforts have been carried out around the world to develop this technology in order to improve electric conversion efficiency, increase reliability by eliminating moving parts, and reduce emissions from coal and gas plants. Closed-cycle liquid metal MHD systems using both single-phase and two-phase flows also have been explored.

Still, more novel applications are in development or on the horizon. For example, recent research has shown the possibility of seawater propulsion using MHD⁶ and control of turbulent boundary layers to reduce drag.⁷ Extensive worldwide research on magnetic confinement of plasmas has led to attainment of conditions approaching those needed to sustain fusion reactions.⁸

In the following sections, we review the basic equations describing coupled MHD behavior as well as some basic MHD phenomena in liquids, gases, and two-phase mixtures. Much of the underlying physics described is common to many of the applications cited above. Also included are discussions of several of the most important applications, together with their special analysis techniques and examples of equipment involved.

11.10.2 Basic Equations

The Full Set of MHD Equations

The MHD Equations. The complete set of MHD equations for a Newtonian, constant-property fluid flow includes the Navier-Stokes equations of motion (i.e., momentum equation), the equation of mass continuity, Maxwell's equations, and Ohm's law. In differential form, they constitute the following system of equations:

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right) = -\nabla p + \mathbf{j} \times \mathbf{B} + \mu_f \nabla^2 \mathbf{u} + \rho \mathbf{g} \quad (11-14)$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \quad (11-15)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (11-16)$$

$$\nabla \times \mathbf{B} = \mu_m \mathbf{j} \quad (11-17)$$

$$\mathbf{j} = \sigma (\mathbf{E} + \mathbf{u} \times \mathbf{B}) \quad (11-18)$$

where the MHD body force $\mathbf{j} \times \mathbf{B}$ is included in the Navier-Stokes equation. The displacement current has been neglected from Ampere's law, which is a valid approximation for nonrelativistic phenomena typical of the response of an inertial liquid. Implicit in Eqs. (11-14) to (11-18) are the following additional relations:

$$\nabla \cdot \mathbf{B} = 0 \quad (11-19)$$

$$\nabla \cdot \mathbf{j} = 0 \quad (11-20)$$

This system of equations is a rich one, describing not only all of the phenomena generally associated with low frequency fluid mechanics and electromagnetics, but also new phenomena not seen in either discipline. Simplifications usually are required to obtain solutions to physical systems of interest. For instance, for quasi-steady flow problems where $\partial \mathbf{B} / \partial t$ is negligible, the electric field can be represented as the gradient of an electric potential ϕ , which simplifies the problem by eliminating vector Eq. (11-16).

Magnetic Induction. The magnetic induction equation is derived easily by taking the curl of Ohm's Law:

$$\nabla \times \mathbf{j} / \sigma = \nabla \times \mathbf{E} + \nabla \times (\mathbf{u} \times \mathbf{B}) \quad (11-21)$$

If $\nabla \times \mathbf{E}$ is replaced by Faraday's Law (Eq. 11-16) and $\nabla \times \mathbf{j}$ is replaced by the curl of Ampere's law (Eq. 11-17), then, using the vector identity

$$\nabla \times (\nabla \times \mathbf{B}) = \nabla (\nabla \cdot \mathbf{B}) - \nabla^2 \mathbf{B} \quad (11-22)$$

we obtain

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \frac{1}{\mu_m \sigma} \nabla^2 \mathbf{B} \quad (11-23)$$

Equation (11-23) is known as the induction equation, and suggests that the motion of a conducting liquid in an applied magnetic field, through the generation of electric current, will induce a magnetic field in the medium. The total field is the sum of the applied and induced magnetic fields. The relative strength of the induced field is characterized by the magnetic Reynolds number ($\text{Re}_m = \sigma \mu_m u L$). The neglect of the induced magnetic field is a valid assumption when Re_m is small.

Dimensionless Parameters. Fluid mechanics equations typically are cast in dimensionless form so that the relative strengths of the different terms can be inferred by the size of any multiplying

factors. The equation of motion (Eq. 11-14) can be written in dimensionless form by making the substitutions

$$\mathbf{j}^* = \frac{\mathbf{j}}{\sigma u_o B_o} \quad (11-24)$$

$$p^* = \frac{p}{\sigma u_o B_o^2 a} \quad (11-25)$$

$$\nabla^* = \frac{1}{a} \nabla \quad u^* = u/u_o \quad B^* = B/B_o \quad (11-26)$$

where a , u_o , and B_o are characteristic values of length, velocity, and applied magnetic field. Characteristic values of the current density and pressure have been selected carefully in order to scale the phenomena of interest; different values could have been selected, leading to different systems of nondimensionalization. Using this system, the equation of motion (excluding gravity) becomes

$$\frac{1}{N} \left(\frac{\partial \mathbf{u}^*}{\partial t} + (\mathbf{u}^* \cdot \nabla) \mathbf{u}^* \right) = -\nabla p^* + \mathbf{j}^* \times \mathbf{B}^* + \frac{1}{Ha^2} \nabla^2 \mathbf{u}^* \quad (11-27)$$

The characteristic parameters Re , Ha , and N are the Reynolds number, the Hartmann number (which is an average measure of the ratio of magnetic to viscous force), and the interaction parameter (which is a measure of the ratio of magnetic to inertial forces). They are defined as

$$Re = \rho u_o a / \mu_f \quad (11-28)$$

$$Ha = a B_o \sqrt{\sigma_f / \mu_f} \quad (11-29)$$

$$N = Ha^2 / Re = a B_o^2 \sigma_f / \rho u_o \quad (11-30)$$

Table 11-19 gives representative values of these characteristic dimensionless parameters, for example, cases of interest. When the Hartmann number and interaction parameter are both sufficiently large, the momentum equation (Eq. 11-27) throughout the bulk of the fluid is often reduced to the simple form

$$\nabla p = \mathbf{j} \times \mathbf{B} \quad (11-31)$$

Whether this inviscid, inertialess approximation is always valid in cases with high Hartmann number and interaction parameter is still the subject of some debate.

Electrical Equations and Ohm's Law.

The Lorentz Force. Underlying the MHD body force is the fact that free charges, with charge q , moving in a magnetic field experience a "Lorentz" force perpendicular to both their velocity and the magnetic field induction:

$$\mathbf{F}_q = q(\mathbf{v} \times \mathbf{B}) \quad (11-32)$$

TABLE 11-19 Typical Values of Re , Ha , N , and Re_m for Several Materials
(Assuming $a = 0.1$ m, $B = 1$ T, $u = 1$ m/s)

	NaK (100°C)	Hg (20°C)	Electrolyte (20°C) 15% KOH	Air (3,000°C) with 2% K
Re	1.6×10^5	9.1×10^5	4.3×10^4	350
Ha	6800	2700	17.5	98
N	290	8.2	7×10^{-3}	27
Re_m	0.30	0.14	1.2×10^{-5}	1.3×10^{-5}

For collisionless particles of mass m , the Lorentz force results in pure harmonic motions in the plane perpendicular to the magnetic field (B_z) with characteristic cyclotron frequency $\omega_c = qB_z/m$:

$$m\dot{v}_y = -qv_x B_z \quad m\dot{v}_x = qv_y B_z \quad (11-33)$$

$$\ddot{v}_y = -\frac{qB_z}{m}\dot{v}_x = -\left(\frac{qB_z}{m}\right)^2 v_y \quad \ddot{v}_x = \frac{qB_z}{m}\dot{v}_y = -\left(\frac{qB_z}{m}\right)^2 v_x \quad (11-34)$$

$$v_y = A_1 \cos \omega_c t + A_2 \sin \omega_c t \quad v_x = A_3 \cos \omega_c t + A_4 \sin \omega_c t \quad (11-35)$$

In contrast, for collisional particles that are forced to follow the fluid velocity $\mathbf{u}$, the Lorentz force acts on electrons and ions in a direction perpendicular to the flow, but in opposite directions for positive and negative charges. The net result is charge separation, leading to the generation of electric fields. The open circuit voltage between electrodes spaced a distance d apart in a conducting fluid is

$$V_{oc} = \int_0^d (\mathbf{u} \times \mathbf{B}) \cdot d\mathbf{l} \quad (11-36)$$

An electric field $\boldsymbol{\varepsilon}$ arises between the electrodes such that $\boldsymbol{\varepsilon} + \mathbf{u} \times \mathbf{B} = 0$, corresponding to the zero-current condition in Ohm's Law (Eq. 11-18). If current is allowed to flow, as a result of some return current path, then the electric field and electrode voltage are reduced due to the electrical resistance of the fluid:

$$\boldsymbol{\varepsilon} = (\mathbf{u} \times \mathbf{B} - \mathbf{j}/\sigma) \quad (11-37)$$

The Hall Effect. In the regime between collisional and collisionless particles, the Hall effect can be important. Usually, the current induced in the fluid is carried predominantly by electrons, which are considerably more mobile than ions. The electron drift velocity, given by

$$\mathbf{j} = n_e e \mathbf{u}_e \quad (11-38)$$

leads to a second component of velocity, and so, according to Eq. (11-32), a secondary force and electric field

$$\boldsymbol{\varepsilon} H = \beta \mathbf{j} \times \mathbf{B} \quad (11-39)$$

where $\beta = 1/n_e e$ is the Hall constant. The current component created by this electric field, that is, the "Hall current," is given by $-\mu_e \mathbf{j} \times \mathbf{B}$, where $\mu_e = \omega\tau/B$ is the electron mobility τ is the electron collision mean-free time. This leads to a more generalized statement of Ohm's Law including the Hall effect:

$$\mathbf{j}/\sigma = (\boldsymbol{\varepsilon} + \mathbf{u} \times \mathbf{B}) - \frac{\mu_e}{\sigma} \mathbf{j} \times \mathbf{B} \quad (11-40)$$

A vector diagram of the electric field components from this relation is shown in Fig. 11-69. Further theoretical discussion of the generalized Ohm's Law can be found in Refs. 9–12.

Generalized Ohm's Law. Ohm's Law, cited above, is a constitutive relationship (for instance, analogous to the equation of state for gases) and as such has a limited range of applicability. Various forms of Ohm's Law can be obtained depending on the approximations made in deriving the current-field relationships from the equations of motion and the interactions of the constituent parts of the fluid. For weakly-ionized gases in thermal equilibrium at moderate temperature, Eq. (11-40) has the equivalent tensor form (neglecting ion current):

$$\mathbf{j} = \hat{\boldsymbol{\sigma}} \cdot (\boldsymbol{\varepsilon} + \mathbf{u} \times \mathbf{B}) = \hat{\boldsymbol{\sigma}} \cdot \boldsymbol{\varepsilon}^* \quad (11-41)$$

or

$$j_v = \sum_k \sigma_v^k \varepsilon_k^* \quad (11-42)$$

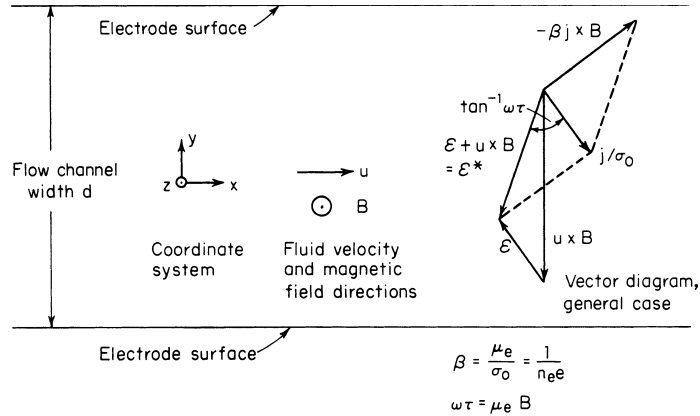


FIGURE 11-69 Vector quantities in the generalized Ohm's Law.

When $\mathbf{B} = z_1 B_z$

$$\hat{\sigma}/\sigma_f = \begin{vmatrix} \frac{1}{1 + \omega^2 \tau^2} & \frac{-\omega \tau}{1 + \omega^2 \tau^2} & 0 \\ \frac{\omega \tau}{1 + \omega^2 \tau^2} & \frac{1}{1 + \omega^2 \tau^2} & 0 \\ 0 & 0 & 1 \end{vmatrix} \quad (11-43)$$

where

$$\begin{aligned} \omega &= \frac{eB}{m_e} && \text{electron cyclotron frequency} \\ \tau &= \frac{\lambda}{c_e} && \text{electron collision mean free time} \\ \omega\tau &= \mu_e B && \text{Hall parameter} \end{aligned}$$

The dimensionless product $\omega\tau$, often called the “Hall parameter,” is an important characteristic number in MHD design. The conductivity tensor is anisotropic due to the Hall component unless $\omega\tau \ll 1$ (typical values for weakly-ionized gases are 1 to 5.) On a microscopic scale, the Hall parameter indicates the average angular travel of electrons between collisions. Typical values are $\lambda \sim 10^{-7}$ m, $c_e \sim 10^5$ m/s, $\tau \sim 10^{-12}$ s, $\omega = 1.76 \times 10^{11} B \sim 10^{12}$ /s for $B = 6$ T. Since the mean free path is inversely proportional to pressure, lower pressure and higher values of B give larger values of $\omega\tau$.

On a macroscopic scale, the value of $\omega\tau$ indicates the relative importance of the Hall field and Hall current. When $\omega\tau = 1$, the total current is directed 45° to the left of the ε^* vector (see Fig. 11-69), and for large values of $\omega\tau$ the current vector is nearly perpendicular to ε^* (predominantly Hall current). In weakly ionized gases, if both the electron ($\omega\tau$) and ion ($\omega_i\tau_i$) Hall parameters are large simultaneously then the angle is reduced. In this case, the conductivity is reduced due to a phenomenon called “ion slip.” Even though τ_i is ordinarily larger than τ_e , ω_i is much smaller than ω_e , such that the product $\omega_i\tau_i$ is usually negligible.

For highly collisional fluids (such as condensed liquids) where $\tau \rightarrow 0$, the Hall current is negligible, and the use of Eq. (11-18) without further modification is satisfactory.

Circuits with Conducting Ducts. For MHD flows in electrically conducting ducts with no external load, a return current can exist in the duct walls (Fig. 11-70). For a uniform flow velocity u , the loop voltage equation is written:

$$\oint \varepsilon \cdot dl = 2b \left(uB - \frac{j_y}{\sigma_f} \right) - 2b \frac{j_w}{\sigma_w} = 0 \quad (11-44)$$

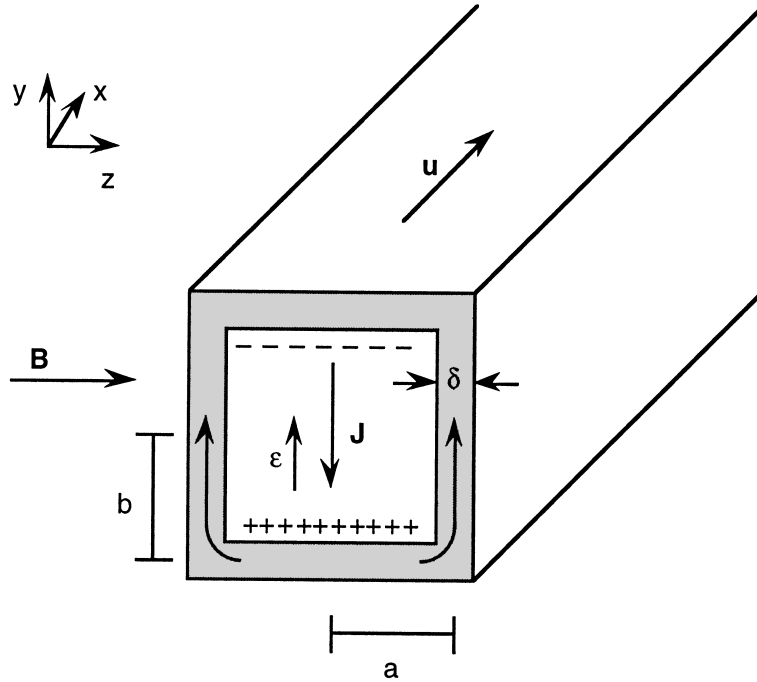


FIGURE 11-70 Current paths in a conducting duct.

where the subscript w denotes values in the wall. Conservation of current dictates:

$$j_y a = j_w \delta \quad (11-45)$$

so that Eq. (11-44) becomes

$$j_y = \sigma_f u B \frac{\Phi}{1 + \Phi} \quad (11-46)$$

where Φ is the “wall conductance ratio”

$$\Phi = \frac{\sigma_w \delta}{\sigma_f a} \quad (11-47)$$

For this type of uniform flow, Eq. (11-31) can be used to estimate the pressure required to drive a flow at velocity u through the duct.

Basic Flow Characteristics and Power Production

Hartmann Flow. Equation (11-46) predicts zero current when the walls are not electrically conducting; however, the no-slip boundary condition on the fluid at the wall, results in a nonuniform channel velocity and the formation of a boundary layer with a reduced $\mathbf{u} \times \mathbf{B}$ emf, allowing a conducting return-current path through the fluid itself.

For one-dimensional, fully developed (hence inertialess) flow, the momentum equation for $u_x(z)$ becomes

$$\frac{dp}{dx} = j_y B_z + \mu_f \frac{d^2 u_x}{dz^2} \quad (11-48)$$

where dp/dx is constant, and Ohm's Law is

$$j_y = \sigma(\varepsilon - u_x B_z) \quad (11-49)$$

It can be shown that the electric field also is constant, so that one can substitute Ohm's Law into the momentum equation and obtain a simple differential equation for u_x :

$$\mu_f \frac{d^2 u_x}{dz^2} - \sigma_f B^2 u_x = \left(\frac{dp}{dx} - \sigma_f B \varepsilon \right) \quad (11-50)$$

The solution to this equation is

$$\frac{u_x}{u_b} = \frac{\text{Ha} \cosh \text{Ha}}{\text{Ha} \cosh \text{Ha} - \sinh \text{Ha}} \left[1 - \frac{\cosh \text{Ha} \frac{z}{a}}{\cosh \text{Ha}} \right] \quad (11-51)$$

where u_b is the bulk average velocity. For large values of the Hartmann number, Eq. (11-51) simplifies to

$$\frac{u_x}{u_b} \approx 1 - \exp \left[\text{Ha} \left(\frac{|z|}{a} - 1 \right) \right] \quad (11-52)$$

Equation (11-52) describes a velocity profile that is nearly flat throughout the duct, with thin boundary layers at the walls where viscous drag forces the flow to zero. The thickness of the Hartmann boundary layer scales as a/Ha . The shape of the Hartmann profile is shown in Fig. 11-71 for a range of Hartmann numbers.

Channel Power and Conversion Efficiency. The total electric power generated internally in a channel is equal to the mechanical work against the MHD body force, which is given by the product of the volume flow rate and pressure drop.

For a distributed medium, the Lorentz force leads to the pressure gradient

$$\nabla p = n \mathbf{F}_q = n q \mathbf{v} \times \mathbf{B} = \mathbf{j} \times \mathbf{B} \quad (11-53)$$

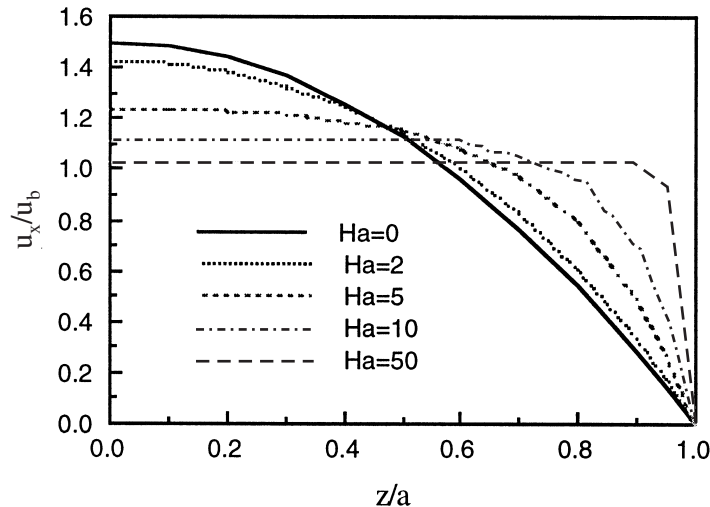


FIGURE 11-71 Normalized Hartmann velocity profiles for $\text{Ha} = 0, 2, 5, 10, 50$.

so that the power density is simply:

$$P_i = \mathbf{u} \cdot \nabla p = \mathbf{u} \cdot (\mathbf{j} \times \mathbf{B}) \quad (11-54)$$

The amount of power delivered to the external load is

$$P_L = \mathbf{j} \cdot \boldsymbol{\varepsilon} \quad (11-55)$$

so that we can write the local electrical efficiency as;

$$\eta_e = \frac{P_i}{P_L} = \frac{\mathbf{j} \cdot \boldsymbol{\varepsilon}}{u_x j_y B_z} \quad (11-56)$$

11.10.3 Liquid MHD

Introduction. As seen above, the presence of the $\mathbf{j} \times \mathbf{B}$ force on the flow of conducting *liquids* can alter the velocity and pressure characteristics of the flow. The interaction with a magnetic field also can significantly affect the onset and character of turbulent fluctuations. These two effects together or individually can dramatically alter the heat-transfer characteristics and fluid drag in closed or open channel liquid flows. Technological applications of such phenomena include cooling systems for magnetic fusion reactors and reduced-drag ship hulls and airplane fuselages.

The MHD force can be applied in such a way that useful work can be done. For example, EM pumps can be designed to precisely control liquid flows, liquid metal flows, in particular, where high temperature and corrosive tendencies prohibit the use of seals in standard mechanical pumps. Such pumps have no moving parts and are extremely reliable. The converse is also possible; MHD generators can produce high currents at low voltages.

This section is concerned with exploring the interaction of the magnetic field with liquid flows both with and without applied electric currents. For incompressible liquids, the equations of Sec. 11.10.2 are valid, with Eq. (11-15) reduced to

$$\nabla \cdot \mathbf{u} = 0 \quad (11-57)$$

A discussion of various applications where such phenomena are encountered is included as well. More comprehensive discussions of many of these subjects can be found in textbooks^{3,13-15} as well as the numerous other references provided throughout this section.

Closed Channel Flows

Fully Developed Channel Flow. The term *fully developed*, used to describe Hartmann flow in Sec. 11.10.2, denotes a condition where the velocity profile is no longer changing (zero derivative) in the main flow direction, that is, a flow that has reached a stable steady state driven by a constant pressure gradient, $P = -dp/dx$. The study of fully developed flow with a constant applied magnetic field is useful because the equations can be solved analytically for a variety of cases, and then can be used as benchmark problems for complete numerical algorithms. In addition, the fully developed solutions predict some phenomena of general interest, especially the existence of different boundary layers, which are important for a general understanding of MHD flows. By controlling the amount of current that can flow in the main body of the liquid, these boundary layers and the MHD boundary conditions exert a significant influence on the velocity profile and pressure drop.

Equations and Boundary Conditions for Two-Dimensional Fully Developed Flow. In a rectangular channel (a round pipe is fundamentally the same), we denote the flow direction as x and restrict the applied magnetic field B_o to be constant and aligned with z , as seen in Fig. 11-70. The MHD equations, Eqs. (11-14), (11-16) to (11-18), and (11-57), can be simplified to the following form:

$$\mu_f \left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + \frac{B_o}{\mu_m} \frac{\partial B_x}{\partial z} = -P \quad (11-58)$$

$$\frac{1}{\sigma_f \mu_m} \left(\frac{\partial^2 B_x}{\partial y^2} + \frac{\partial^2 B_x}{\partial z^2} \right) + B_o \frac{\partial u}{\partial z} = 0 \quad (11-59)$$

where the velocity vector has only one component in the x -direction, and the magnetic field is the sum of the constant applied field in the z -direction and the small field induced in the x -direction.

$$\mathbf{u} = [u(y, z), 0, 0] \quad \mathbf{B} = [B(y, z), 0, B_o] \quad (11-60)$$

Terms quadratic in B have been discarded as small, an assumption equivalent to assuming small Re_m , so that B really represents a stream function for the electric current, where

$$\mu_m j_y = \frac{\partial B_x}{\partial x} \quad \mu_m j_z = -\frac{\partial B_z}{\partial z} \quad (11-61)$$

Walls parallel to the magnetic field (i.e., “side walls”) are located at $y = \pm b$, and walls perpendicular to the field (i.e., “Hartmann walls”) are located at $z = \pm a$. The boundary condition for the velocity is the standard fluid-mechanical no-slip condition:

$$U = 0 \quad (\text{at all walls}) \quad (11-62)$$

For certain boundary conditions on the induced field B , analytical solutions exist in the form of infinite series to the system. Much of the classic work in the 1950s and 1960s focused on solving these equations either exactly or approximately by expanding one dimension in an appropriate set of eigenfunctions. Some boundary conditions for the induced field are summarized in Eqs. (11-63) to (11-65). These conditions are derived by considering the behavior of the normal n and tangential s current at the wall, and using Eq. (11-61) to phrase these conditions in terms of the induced magnetic field.

$$B = 0 \quad \text{electrically insulated wall}^{16,17} \quad (11-63)$$

$$\frac{\partial B}{\partial n} = 0 \quad \text{perfectly conducting wall}^{18} \quad (11-64)$$

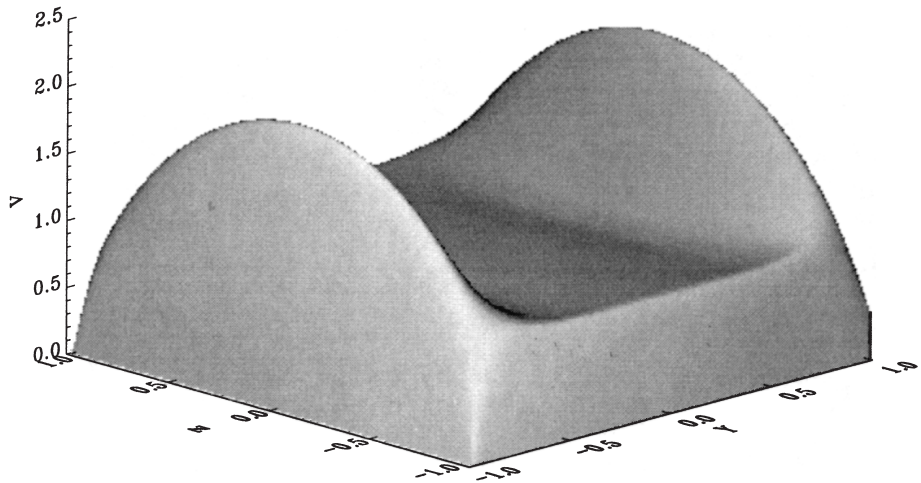
$$a \Phi \frac{\partial B}{\partial n} - B = 0 \quad \text{thin conducting walls}^{19-21} \quad (11-65)$$

Inviscid Core Flow and Boundary Layers. When Ha is large, the infinite series solutions cited above show (see Fig. 11-72) the existence of a flat, inviscid core region in the central section of the duct, bordered by different types of viscous boundary layers near the Hartmann walls and side walls²². In this core region, the driving force of pressure is balanced entirely by the MHD force, $\nabla p = \mathbf{j} \times \mathbf{B}$. The curl of this equation implies that $(\mathbf{B} \cdot \nabla)\mathbf{j} = 0$, indicating that the current density is constant along (applied) field lines in the core. A constant pressure and a constant current produce a flat constant velocity in the core region.

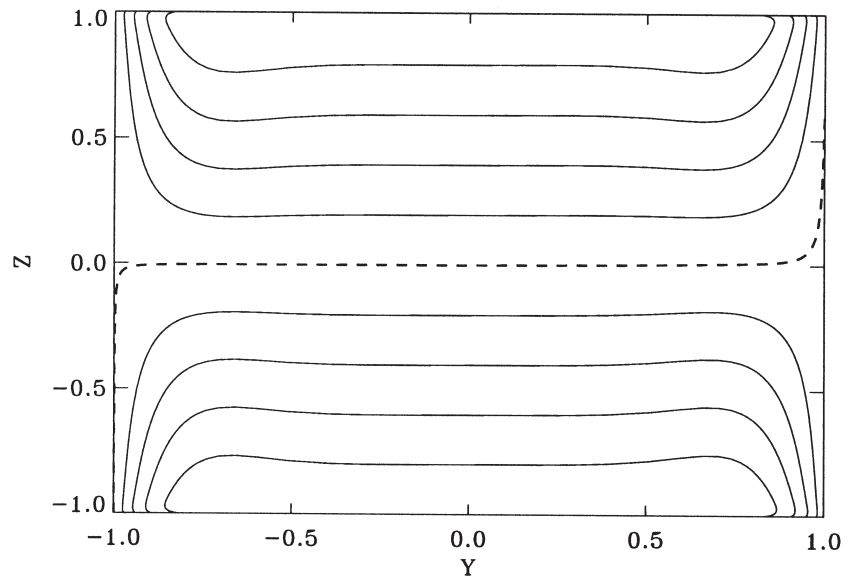
On the Hartmann walls at $z = \pm 1$, a Hartmann layer forms (similar to that seen in the one-dimensional example of “Basic Flow Characteristics and Power Production” under Sec. 11.10.2), as shown in Fig. 11-72. Hartmann layers have thickness of a/Ha , and join smoothly to the core value of the velocity. The Hartmann layer serves as a region where electric currents induced in the core flow in the y -direction can return and complete the current loop. This role as current return path makes the Hartmann layer an active boundary layer, one whose properties control the amount of flow possible in the core region. If the Hartmann wall is electrically conducting, the electric current will flow in the wall as well, and the influence of the Hartmann layer on the core flow will be accordingly reduced.

In most cases, it is the combined conductivity of the Hartmann layer and Hartmann wall that determines the MHD resistance to the fluid flow in the core, and so governs the pressure gradient P (i.e., the pressure gradient required to drive the flow at a given average velocity). In an electrically insulated channel with laminar flow, the increase in P is due to increased shear friction at the walls as a result of the modification of the parabolic laminar velocity profile. The average electromagnetic force in this case is zero since all the current induced in the flow closes through boundary layers in the fluid itself. For large Ha with insulated walls, P increases linearly with Ha . For electrically conducting channels, the net electromagnetic force is no longer zero, but can in fact be quite large. For a perfectly conducting channel with large Ha , P increases proportionally with Ha^2 .

On the side walls at $y = \pm 1$, one observes the formation of a different type of boundary layer, alternately known as a “side layer,” shear layer,” or “Shercliff layer.” The interpretation of these layers



(a)



(b)

FIGURE 11-72 Flow profiles in a square ($\beta = 1$) duct with $Ha = 75$, insulated side walls, and Hartmann walls with $\Phi = 0.1$: (a) velocity profile; (b) electric current paths.

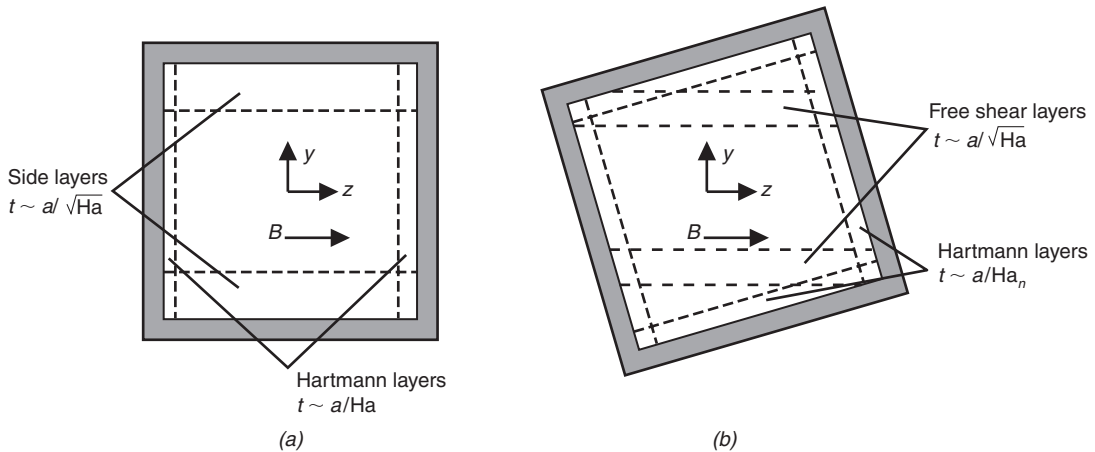


FIGURE 11-73 Boundary layers in a rectangular duct (a) aligned with and (b) oblique to an applied magnetic field.

is a region where mismatched electric potentials equalize, sometimes with a significant jet of liquid when the Hartmann walls are electrically conducting. (This is the case pictured in Fig. 11-73). These jets can carry an appreciable portion of the net mass flux under certain cases. The thickness of side layers is of order $a/Ha^{1/2}$, which is much greater than that of the Hartmann layer. Thus, in most cases (except when the Hartmann walls are highly conducting but the sidewalls are not), the electrical resistance of the side layers does not add significantly to the total resistance of the return current path, and so does not influence the core velocity. For larger Hartmann numbers on the order of 10^3 or 10^4 , the flow in the core region drops almost to zero, and the velocity jets can be up to a factor of Ha times the core flow velocity. Obviously, such velocity structures can be very important in determining heat transfer in liquid metal coolant pipes, as well as affecting corrosion, mass diffusion, and other important physical processes.

Hartmann layers will form on any wall that has a normal component of B_0 , but shear layers form only along the magnetic field lines. Thus, if the channel is not perfectly aligned with B_0 , then all walls will have Hartmann layers, and the shear layers will detach from the wall and form about the magnetic field line that intersects the corner of the duct (see Fig. 11-73b). Shear layers that extend into the fluid are known as *free shear layers*.²³

Developing Flows, Variable Fields, Variable Duct Sizes, and Entrance Effects. Few practical MHD flows are fully developed over their entire length. Developing flows are inherently three-dimensional since the motion, electric currents, and magnetic field and its gradients invariably are oriented in different directions. Sudden expansion and other change in the magnetic field, channel shape, or channel electrical conductivity can result in significant changes in velocity profiles and additional three-dimensional pressure drops. Even local regions of reversed flow are possible in different MHD duct flow configurations, as in the case of a locally conducting crack in a pipe wall covered with an electrical insulator coating.

Only when the flow has advanced sufficiently far from these disturbances will it again become fully developed and assume the characteristic velocity profiles and pressure drops discussed above. A rigorous treatment of the effects of changes in field and geometry possible in MHD machines are available in the literature.^{3,13,14} One example of practical interest is the entrance of a rectangular duct into a magnetic field (typical of MHD conduction pumps discussed later), and the so-called M-shaped velocity profile. Use of the core flow approximation, described in more detail below, is a powerful tool for analyzing these MHD phenomena at large Ha .

Duct Flows in Varying Magnetic Fields. Consider a rectangular duct with the orientation shown in Fig. 11-70, but assuming that at $x = 0$, the magnetic field changes abruptly from zero to some

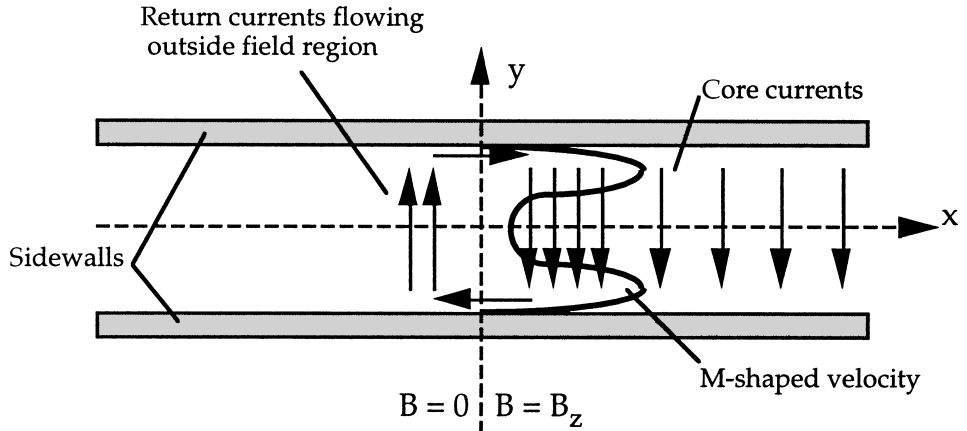


FIGURE 11-74 Simplified current paths and velocity profile for duct in a variable magnetic field.

value B_z . (The case of a more gradual transition does not fundamentally change the description.) As in the fully developed case, the $\mathbf{u} \times \mathbf{B}$ emf induces a current in the negative y -direction. At the sidewalls, the current can turn into the z -direction and then flow to the Hartmann walls, but now it can also turn (more easily) into the x -direction and return to the other sidewall through the region of no field directly adjacent to the region of high field (see Fig. 11-74). The same electric field set up by the charge separation that drives return current through the Hartmann layers (walls) will drive this current in the no-field region. Thus, an additional current closure path exists, and so more core current can flow in the high field region as compared to the corresponding fully developed flow in a region of constant B_z . This additional current results in a greater pressure drop, usually denoted Δp_{3D} .

The current in the x -direction near the sidewalls also causes a distortion of the velocity profile near the region of changing B_z . The j_x current, which is positive in the upper part of the channel ($y > 0$), will induce a force in the negative y -direction near the sidewall. This force will essentially pressurize the sidelayer, and cause a velocity jet to form in the sidelayer. A similar result occurs in the lower half ($y < 0$) plane. The result is a velocity profile called “M-shaped,” where the velocity is reduced in the core due to increased $\mathbf{j} \times \mathbf{B}$ forces, but increased in the sidelayers. This looks very similar to the sidelayer jets that can occur in fully-developed flow when the Hartmann walls are electrically conducting, but the M-shaped profile forms in the developing region even when the entire channel is nonconducting. Like the fully developed sidelayer jets, the M-shaped velocity profile is shorted out when the sidewalls are highly conducting, since the j_x current preferentially flows in the walls in this case, and no force is induced in the liquid itself. The same effect occurs at the exit of a magnetic field, and even if the field is more gradually varied.

Mathematically, the formation of the M-shaped velocity profile can be understood by taking the curl of the steady inviscid equation of motion:

$$\nabla \times \{\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \mathbf{j} \times \mathbf{B}\} \quad (11-66)$$

and considering the z component of vorticity:

$$\rho u \frac{\partial \omega_z}{\partial x} \cong -j_x \frac{\partial B_z}{\partial x} - B_z \frac{\partial j_y}{\partial y} \quad (11-67)$$

Both terms on the right hand side of Eq. (11-67) will be negative in the upper right quadrant of Fig. 11-74, and positive in the lower right quadrant. These sources of z -directed vorticity can be thought of as swirling motion that decelerates the center and shifts fluid to the sidelayers, causing the formation of the velocity jets. It is easily seen that the formation of sidelayer jets in fully

developed flow is also governed by the last term in the above equation, which is present in regions of constant B_z as well.

General Core Flow Equations. For high conductivity liquids like liquid metals, calculations at high Ha can become very difficult unless simplifying approximations are made. One such approximation indicated by the above discussion is the so-called core flow approximation, where the momentum equation is simplified to

$$\nabla p = \mathbf{j} \times \mathbf{B} \quad (11-68)$$

In 1968, Kulikovskii²⁴ showed that the core equations (Eqs. 11-18, 11-20, 11-57, and 11-73) could be manipulated in such a way as to reduce the solution for any flow geometry without side-walls or internal shear layers to, at most, 4 two-dimensional partial differential equations. In addition, the magnetic field is assumed to be externally applied ($Re_m = 0$). The unique features of these equations allow us to separate components of velocity and current into components parallel and perpendicular to the magnetic field:

$$\mathbf{j}_\perp = \frac{B}{B^2} \times \nabla p \quad (11-69)$$

$$j_\parallel = \int \left(\mathbf{B} \times \nabla \frac{1}{B^2} \right) \cdot \nabla p \, dl + A_1 \quad (11-70)$$

$$\mathbf{u}_\perp = -\frac{1}{\sigma B^2} \nabla p + \frac{\mathbf{B}}{B^2} \times \nabla \varphi \quad (11-71)$$

$$u_\parallel = \int \left[\left(\mathbf{B} \times \nabla \frac{1}{B^2} \right) \cdot \nabla \varphi + \left(\nabla p \cdot \nabla \frac{1}{\sigma B^2} \right) + \frac{\nabla^2 p}{\sigma B^2} \right] dl + A_2 \quad (11-72)$$

$\mathbf{j}_\perp$ is obtained by taking the cross-product of $\mathbf{B}$ with the momentum equation (Eq. 11-68). Similarly, $\mathbf{u}_\perp$ is obtained by taking the cross-product of $\mathbf{B}$ with Ohm's Law [Eq. 11-18]. $j_\parallel$ and $u_\parallel$ are obtained by integrating the conservation laws (Eqs. 11-20 and 11-57 along the magnetic field direction, dl , defined by $\nabla_\parallel = d/dl$).

Finally, the electric potential can be related to the parallel current:

$$\sigma \frac{\partial \varphi}{\partial l} = j_\parallel \quad (11-73)$$

$$\sigma \varphi = \iint \left(\mathbf{B} \times \nabla \frac{1}{B^2} \right) \cdot \nabla p \, dl' + A_1 l + A_3 \quad (11-74)$$

The boundary conditions at the walls completely determine the unknown functions (A_1, A_2, p , and ϕ). There are four boundary conditions. Zero mass flux into the walls and conservation of current are applied twice for each field line: once where the field line enters the fluid and once where it exits.

$$\mathbf{u} \cdot \hat{n} = 0 \quad (11-75)$$

$$\Phi \nabla^2 \varphi = \mathbf{j} \cdot \hat{n} \quad \text{for conducting ducts} \quad (11-76)$$

$$\frac{1}{Ha} (\nabla \times \mathbf{u}) \cdot \hat{n} = \mathbf{j} \cdot \hat{n} \quad \text{for nonconducting ducts} \quad (11-77)$$

This method has been successfully applied to the solution of a number of basic geometries in Ref. 25. and formulated in a very general fashion in Ref. 26. For symmetric problems, the constants A_1 and A_2 can be eliminated. The constant A_3 can be replaced by the evaluation of φ at any location along l . (For example, A_3 can be replaced by φ_w , the potential at one wall.) In this case, only two partial differential equations remain for p and φ_w .

The resulting set of linear partial differential equations can be solved using any appropriate numerical technique. A finite difference representation was applied and SOR was used to solve the resulting system of algebraic equations.²⁵ Corrections for sidelayers and internal shear layers also have been developed.²⁷

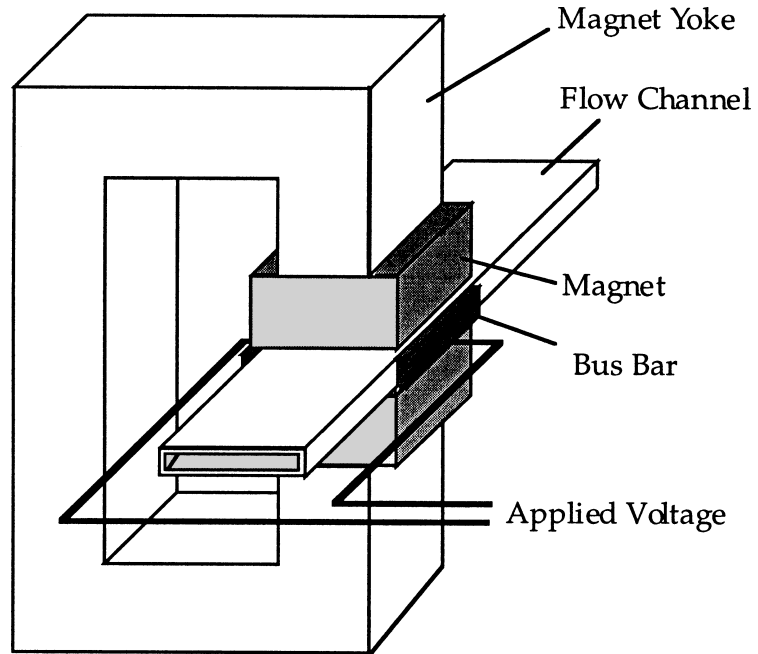


FIGURE 11-75 Generic dc conduction pump with rectangular channel.

EM Pumps and Flowmeters. One of the more practical uses of the MHD force is in pumping systems, where electrical energy is converted directly into force on the working liquid. EM pumps (as they are commonly known) have been in existence for many years, and many different designs have been successfully developed and employed. A generic conduction style pump is shown in Fig. 11-75. Another common MHD device is the EM flowmeter, where the potential induced by fluid motion is measured and used to infer the average flow rate.

These devices can be constructed with no moving parts and no direct contact with the working liquid. This is a distinct advantage if high temperature and/or corrosive liquids must be handled. The absence of seals or moving parts leads to a highly reliable system. In addition, EM pumps are typically controllable, and even reversible, by varying the magnitude and direction of the applied current.

MHD Flowmeters. Equation (11-36) suggests that the voltage induced by the $u \times B$ emf would provide an ideal method by which one could measure the average flowrate of a conducting liquid. However, it is impossible to achieve a completely open-circuit configuration as described by Eq. (11-36), as return current will flow in pipe walls and boundary layers of all finite size channels. Some accounting for these return currents must be included when determining a relation for the voltage signal as a function of the flow velocity. Ohm's Law, as written in Eq. (11-37), shows the effect of return currents on the measured voltage signal in a rectangular channel like that in Fig. 11-69:

$$-\varepsilon = \varphi/2b = uB - j/\sigma \quad (11-78)$$

where φ is the voltage signal. Any core current allowed to flow, then, reduces the measured voltage signal by some amount. Using the result of Eq. (11-46) for the core current density, we see that the voltage signal is

$$\varphi = \frac{2buB}{1 + \Phi} = \frac{QB}{2a(1 + \Phi)} \quad (11-79)$$

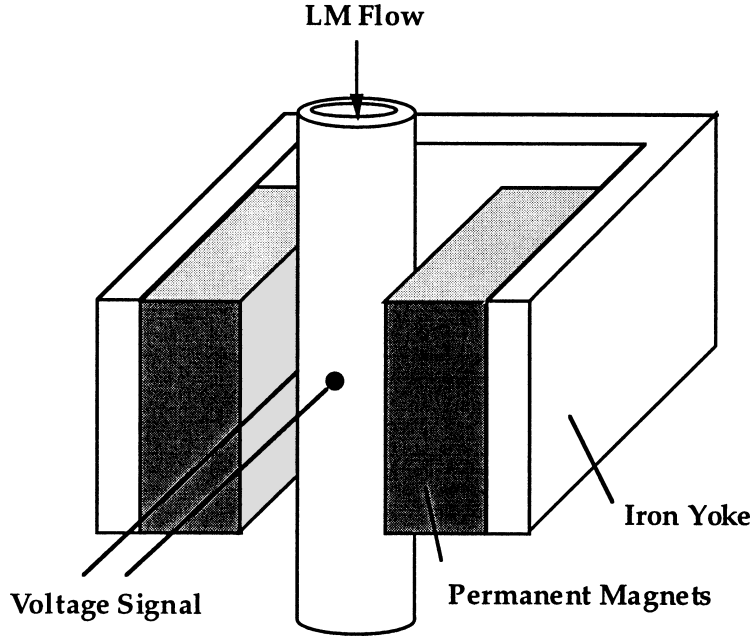


FIGURE 11-76 Generic dc EM flowmeter.

which is independent of the electrical conductivity of the liquid, except as it appears in the wall conductance ratio Φ . This means that many moderately conducting liquids can also be measured by this method, especially when an electrically insulated channel can be used. (For insulated channels, substitute Ha^{-1} for Φ in Eq. 11-79.) For common laboratory and industrial values of the flow rate Q , magnetic field induction, and duct dimensions, the measured voltage is typically in the range of hundreds of microvolts to several millivolts.

Most MHD flowmeters do not use rectangular channels, but instead use round pipes that can fit easily into standard piping systems, like that shown in Fig. 11-76. Reference 28 suggests the following relation for the volumetric flowrate in a pipe made of an electrically conducting material:

$$Q = 3162 \frac{k_4}{k_1 k_2 k_3} \frac{d\varphi}{B} \quad (11-80)$$

where Q is in units of gpm, B is in Gauss, the inside pipe diameter d is in inches, and the electric leads to measure φ are attached to the outside of the pipe wall.

Equation (11-80) takes into account, in the form of semiempirical multiplicative constants k_{1-4} , several nonideal effects that were ignored in Eq. (11-78). k_1 is the pipe-wall current shunting correction factor defined as

$$k_1 = \frac{2dD}{D^2 + d^2 + \frac{\sigma_w}{\sigma_f}(D^2 - d^2)} \quad (11-81)$$

where D is the outside pipe diameter, also in inches.

Poorly conducting liquids tend to have a k_1 correction factor that deviates significantly from unity, meaning that the electrical signal is lower for the same flowrate and so more difficult to measure accurately. k_2 is the magnetic field end-effect correction factor. It is empirically obtained as a function of the

magnet pole piece length L . Typical values are given in Table 11-20. k_3 is the magnetic material temperature correction factor, which accounts for changes in the magnetic field as a function of temperature of the permanent magnetic material or electromagnet windings. The manufacturer of such materials typically provides the appropriate temperature correction factors. k_4 is the pipe thermal expansion correction factor, which accounts for changing pipe sizes as a function of temperature and can be expressed as $k_4 = 1 + \gamma (T - T_o)$, where γ is the thermal expansion coefficient for the pipe material. For 304 stainless steel, the value of γ is $9.6 \mu\text{-in/in F}$.

TABLE 11-20 Magnetic Field End Effect Correction Factors²⁸

L/D	k_2
1.5	0.91
1.9	0.96
2.4	0.98
3.0	0.99

The idea behind these simple dc flowmeters has evolved into more complicated implementations where pulsed dc or pulsed ac electromagnets are used to sample the flowrate at some pulse rate. The pulsed electromagnet devices have lower power consumption and lower heat generation in the electric coils. These devices are available commercially²⁹ with all manner of pipe materials and sizes and can be inserted easily into existing piping configurations. Small units ($d \approx 1$ in) have accuracies of around 1% at full scale. The accuracy tends to improve as pipe sizes become larger.

Conduction Pumps. Liquid metal conduction pumps, or “Faraday” pumps, consist of a rectangular channel in the gap of a magnet (either a permanent or electromagnet) where an electric current is passed through the conducting liquid perpendicular to the field. The resulting $\mathbf{j} \times \mathbf{B}$ force drives the flow. This type of pump is a conceptually simple extension of the rectangular duct flows discussed above with sidewalls replaced by electric bus bars connected to an outside voltage source, which drives current in the direction opposite to the $\mathbf{v} \times \mathbf{B}$ emf.

To understand the pressure and flowrate behavior of a simplified conduction pump, pictured in Fig. 11-75, it is helpful to represent the pump by an equivalent electrical network Fig. 11-77. Here, R_{LM} is the effective resistance of the liquid in the channel, R_{Loss} is the resistance of any loss paths such as the channel walls and fringing paths outside the magnetic field area, and E_i is the voltage induced in the flow, which works against the applied current I_a . Assuming slug flow of flow rate Q in a rectangular pumping channel of flow length L within the field, with walls of thickness δ_w and electrical conductivity σ_w , the following approximations can be applied:

$$R_{LM} = \frac{b}{La\sigma_f} \quad R_{Loss} = \frac{b}{L\delta_w\sigma_w} \quad (11-82)$$

$$I_{LM} = \frac{2a\Delta p}{B} \quad E_i = 2buB = \frac{QB}{2a} \quad (11-83)$$

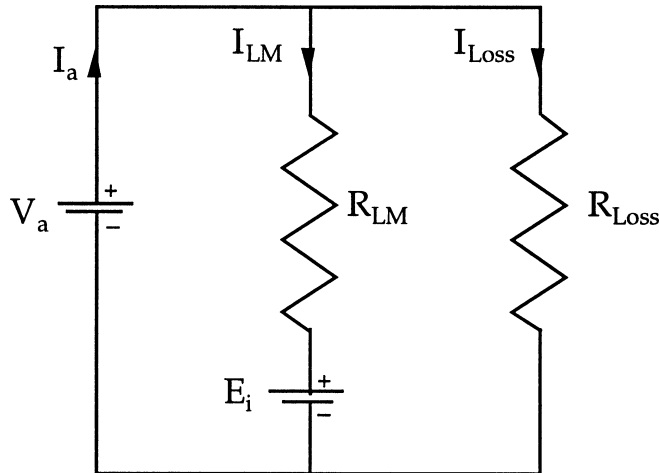


FIGURE 11-77 Circuit network equivalent of a conduction pump.

The duct geometry used is the same as in Fig. 11-70, and the R_{loss} term only takes into account current losses through conducting Hartmann walls for simplicity. The circuit then can be solved to give the following linear relationship between pressure and flow rate:

$$\Delta p = \frac{BAI_a/2a - B^2LQ\Phi\sigma_f}{A(1 + \Phi)} \quad (11-84)$$

where $A = 4ab$ is the flow cross-sectional area, and Φ is the wall conductance ratio defined in the usual way as in Eq. (11-47). This relationship is plotted in Fig. 11-78 for a small conduction pump with various values of Φ . We see the obvious need for thin and/or low conductivity walls in the pumping channel structure in order to maximize the pumping power. In the case of $\Phi = 0.1$, at flowrates above 7.51/s, all of the applied current is simply shunted through the walls, as the induced emf is larger than the applied voltage. Current flow in the core is reversed, and MHD drag, instead of pumping, results.

The applied voltage for this particular pump, assuming $Q = 10$ l/s and $\Phi = 0.01$, is only 213 mV. The inherently low voltage and high current of conduction pumps is one of their disadvantages, since they require special power supplies capable of coupling efficiently to such a load. Possible power supplies that are more efficient than standard transformer-rectifier systems include homopolar and unipolar generators, which can be up to 80% efficient. To increase the voltage of the load somewhat, it is common to run the field coil windings of the electromagnet in series with the LM section, so that only one supply (albeit at a greater power level) is needed.

The power dissipated in the conduction pump system for our example above is

$$P_a = 0.215 \text{ V} \cdot 1500 \text{ A} = 322 \text{ W} \quad (11-85)$$

The power delivered to the fluid ($Q \cdot \Delta p$) is $P_f = 0.01 \text{ m}^3/\text{s} \cdot 25.7 \text{ kPa} = 257 \text{ W}$. This gives an efficiency of 81%. A formula for the electrical efficiency in the general case is easily constructed in terms of either the applied voltage or the applied current:

$$\eta_e = \frac{Q\Delta p}{V_a I_a} = \frac{BQ}{2aV_a \left(1 + \frac{\Phi}{1 - BQ/2aV_a}\right)} = \frac{2bI_a - BLQ\sigma_f\Phi}{2bI_a \left(1 + \frac{2bI_a}{BLQ\sigma_f}\right)} \quad (11-86)$$

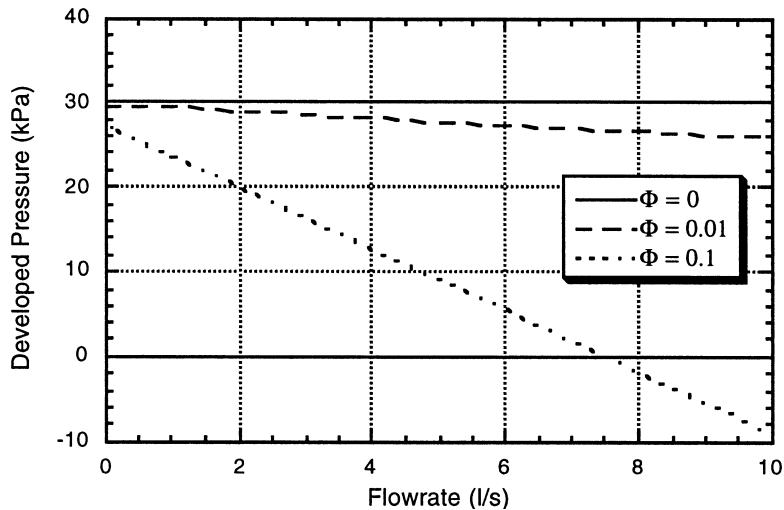


FIGURE 11-78 Pressure head of a conduction pump for various wall conductance ratios and the following parameters: $a = 5$ cm, $b = 15$ cm, $L = 30$ cm, $B = 2$ T (iron core electromagnet), $I_a = 1,500$ A, and $\sigma_f = 10^6 \Omega \text{ m}$.

However, the losses in the wall included in this simple calculation are not the only losses the conduction pump experiences. Applied current usually fringes outside the area of the applied magnetic field where it induces no $\mathbf{j} \times \mathbf{B}$ force. Energy is lost to the damping of turbulence and restructuring of the average velocity profile as the liquid enters the magnetic field area. Energy losses occur due to friction of the flow on the channel walls and the applied magnetic field is altered by the field induced by the applied current itself. All of these effects decrease the net efficiency of conduction pumps to the order of 15% to 20% for small pumps, and 40% to 50% for larger pumps. Including losses in generators and field windings, the bus bar efficiency for liquid metal conduction pumps varies from 10% to 40%, increasing with pump size.³⁰

As seen from Eq. (11-86), even in the absence of losses other than the resistance of the LM itself, the electrical efficiency of the system is equal to $\eta_e = \eta_{\text{ind}} = 2buB/V_a$, which is the induction efficiency, that is, the ratio of induced voltage due to the $\mathbf{u} \times \mathbf{B}$ emf to the applied voltage V_a .

Induction Pumps. An alternative to the conduction pump is the induction pump, where electric currents are induced in the liquid metal by means of a time-varying magnetic field, producing a $\mathbf{j} \times \mathbf{B}$ force with the instantaneous field to drive the flow. Many types of induction pumps are possible. Here we focus on the flat linear induction pump and the annular linear induction pump. The advantage of induction pumps is that they can be driven easily by single-phase or 3-phase ac power sources, possibly with a variable transformer for control of the flow rate. Typical disadvantages are greater power losses and the need for electrical insulation at high temperatures close to the working liquid.

The flat linear induction pump, or FLIP is conceptually similar to an ac induction motor. The 3- ϕ winding, however, produces a sliding, rather than rotating magnetic field, which tends to pull the fluid along. The action of this class of pump is easily pictured by contemplating the simplified induction pump shown in Fig. 11-79. If the peak vertical magnetic field is sliding to the right, leaving behind a slightly reduced magnetic field, a current loop will be induced. This induced current tries to maintain the field at its original strength. The induced current into the page will be in a region of stronger magnetic field than the current coming out of the page, since the field peak is propagating to the right, so the net $\mathbf{j} \times \mathbf{B}$ force will be to the right.

The disadvantage to these systems is that in order to have a relatively wide channel for liquid flow, the gap between the stators must be larger than that in induction motors, and the field losses are

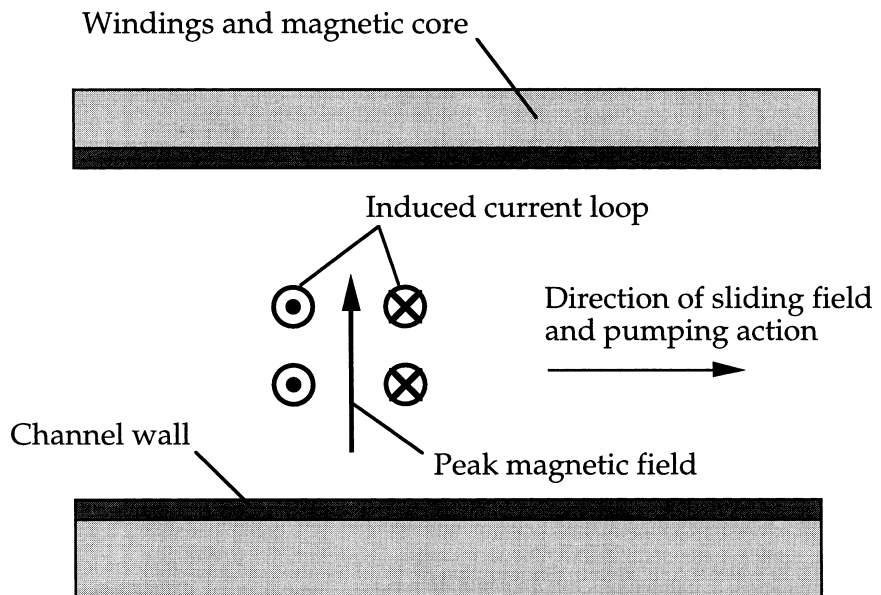


FIGURE 11-79 Operation of an induction pump.

relatively higher. In addition, field fringing occurs at the boundaries of the wide, flat channel where the magnetic core stops. One-sided stator induction pumps are also possible, but losses will be even higher. Such systems have uses as EM stirrers and for ship propulsion, as will be discussed later.

The annular linear induction pump (ALIP), sometimes called an Einstein-Szilard pump, is a modification of the FLIP so that end effects do not cause additional field losses. The ALIP consists of an annular flow region with an internal magnetic core. Induced currents flow in a continuous loop through the liquid, and no core edge exists off which magnetic fields fringe. In essence, an ALIP is like a FLIP that has been bent around until the free ends are joined.

Design guidelines and photographs of various styles of EM induction pumps are available in Ref.³¹.

MHD Ship Propulsion. Another potential use of EM pumping technology is MHD thrusters for ship propulsion. Seawater has a moderate electrical conductivity, of the order of $5 (\Omega \cdot \text{m})^{-1}$, and under the appropriate set of conditions can be pumped by the Lorentz force. Care must be taken to avoid large losses in conducting walls in this application, but this is more easily done when the working fluid is seawater rather than high temperature liquid metals.

Conduction pump thrusters³² are more commonly envisioned for MHD ship propulsion because of the difficulty inducing large currents in poorly conducting water. Using the above equations for the conduction pump, we find that the ideal conduction pump thruster will deliver a power to the liquid equal to

$$P_w = F_{EM} u = (1 - \eta_e) \eta_e \frac{\sigma_f V_a L a}{b} \quad (11-87)$$

For a given size channel (usually limited by the size of the craft under consideration), a given applied voltage (usually limited by the power supply aboard the craft, e.g., a battery), and a given liquid (seawater), the mechanical power is maximized at $\eta_e = 50\%$. This means one-half of the electrical power supplied is lost as Ohmic heating. Thruster designers must decide whether their goal is to maximize mechanical power or to minimize energy consumption.

For a moderately sized submarine (10-m diameter, 83-m length) using four conduction thrusters with length $L = 55$ m, $b = 5$ cm, and $a = 15$ cm, a 5-T field is sufficient to generate reasonable thrust and efficiency. At a speed of 36 knots, the thrusters will consume about 66 MW of electric power, requiring a 200 MW thermal nuclear plant with a typical thermal conversion efficiency (excluding power needed for other boat systems). This level of power is not unreasonable for a submarine of this size. Superconducting magnets are necessary for this field strength and core size, since the Ohmic losses in resistive magnets would be unacceptable.

At least one design using an induction pump thruster has been advanced. The “ripple motor” described by Mitchell and Gubser³³ utilizes a 3- ϕ ac solenoidal winding around a core of seawater. An annulus of liquid sodium or other liquid metal serves as an intermediate layer separated from the seawater by a flexible membrane. The thickness of the sodium layer is matched to the skin depth of the ac field. The traveling magnetic field sets up a traveling pressure wave in the sodium and thus a traveling wave on the flexible membrane. This wave pushes along the seawater and eventually ejects it out of the trailing end of the thruster, providing the thrust.

Turbulence in Liquid MHD Flow. MHD forces can have a large effect on the turbulence structure of liquid flows. Not only does the induction of a current density result in Ohmic dissipation of energy, a new energy loss mechanism that augments the viscous dissipation, but the field also changes the average velocity profiles as discussed in previous sections, resulting in new turbulence-creation scenarios as compared to non-MHD flows. The magnetic field is typically thought to *laminarize* already turbulent flows or to prevent the transition to turbulence in laminar flows. In electrically conducting channels,¹³ core velocity fluctuations are damped for values of $\text{Ha}/\text{Re} > 0.008$. Near the sidewall jets, though, turbulent fluctuations increase, indicating that the strong velocity jets, like those depicted in Fig. 11-71, are unstable and periodically break down. For $\text{Ha}/\text{Re} > 0.02$, these fluctuations are also damped (or at least unresolved due to boundary layer thinning), and the liquid flow becomes effectively laminar.

Electrically insulating channels exhibit a change, as the field is applied, from standard turbulence to a quasi-two-dimensional turbulence, where the vorticity of the turbulent fluctuations is predominantly aligned with the direction of the field. Turbulence fluctuations of this type can be quite long-lived

and probably result from the reorganization of the flow as it enters into a magnetic field. The formation of M-shaped velocity structures, which then decay into rotating vortices, is the source of such fluctuations. In an infinitely long, electrically insulated channel, all turbulence fluctuations are eventually damped when $Ha/Re > 0.008$.

Control of turbulence near the wall of a ship or submarine can in theory reduce the overall drag on the structure. Early work on MHD channel flows³⁴ showed that the pressure drop in an initially turbulent LM duct flow could be reduced by the judicious application of a magnetic field. (Too strong a field will result in increased MHD drag, as discussed above.) For the control of turbulence near ships, one must contend with the fact that seawater is a poor electrical conductor, and that induced currents alone will not dissipate enough energy to stabilize a turbulent boundary layer. Instead, currents must be generated by an applied voltage.

One such scheme to reduce drag on, and radiated noise from, a flat plate is to construct the surface with alternating north and south pole magnets interspersed between positive and negative electrodes (see Fig. 11-80). The crossing lines of magnetic field and current induce a $\mathbf{j} \times \mathbf{B}$ force in the streamwise direction, acting as a sort of one-sided conduction pump. Preliminary experiments³⁵ have shown that turbulent fluctuations can be reduced over much of the boundary layer when the modified interaction parameter ($N^* = j_o B_o \theta / 0.5 \rho u_\tau^2$, where j_o , B_o are the current, field at the electrode, magnet surface, and θ and u_τ are the standard momentum thickness and friction velocity of the boundary layer, respectively) is order one or larger. The boundary layer is found to approach an asymptotic value, rather than growing indefinitely and breaking down due to instability. Work in this area by a number of researchers is continuing.

Open Channel Flows. Open channel flows of liquids in magnetic fields are of interest for metallurgical and welding applications where melts and melt layers are influenced by electric currents and applied magnetic fields. There is also interest in open channel MHD flows in magnetic fusion energy reactors where it might be advantageous to have high heat flux surfaces facing the burning plasma be covered with a flowing liquid metal layer.³⁶ When the problem of open channel MHD flows is examined closely, one finds that the complicated motion of closed-channel duct flows described above becomes even more complicated when the liquid interface (free surface) is allowed to move in response to MHD forces.

The interfacial boundary condition for open-channel flows requires that the tangential component of the viscous stress must be continuous. The term “free surface” implies the less general case where the liquid surface is unhampered by friction with a gas phase outside the liquid region, and so the tangential component of the stress vanishes. However, this condition is changed in MHD flows

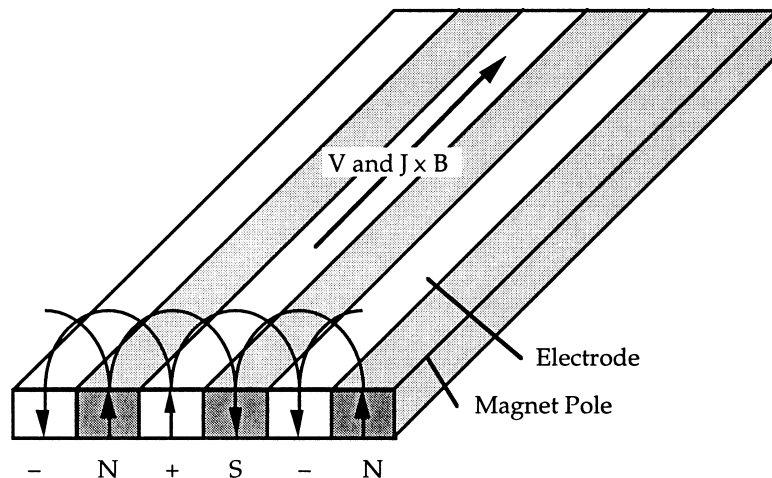


FIGURE 11-80 Turbulence reduction technique for seawater: alternating magnets and electrodes.

where the total stress, the sum of the tangential viscous and magnetic stresses, must be continuous. The magnetic stress is represented by the Maxwell stress tensor (found elsewhere in this handbook), and can exist in vacuum as well as in conducting media. This EM stress vanishes for temporally and spatially uniform magnetic fields, but needs to be considered in the general case.

Some simple cases of flow down an inclined plate are analyzed by Alpher,³⁷ Aitov,³⁸ Morley³⁹ and others. It is seen that for a magnetic field normal to the surface of a very wide, long plate, a half-Hartmann velocity profile forms in the surface normal direction. The flow is essentially that shown in Fig. 11-70 split open, where $z = 0$ is the free surface and $z = 1$ is the back plate. The Hartmann layer on the plate is exactly the same as one would expect in channel flow, and provides a return-current path for currents generated in the core. Also similar to flow in ducts, the modification of the velocity profile and the unbalanced $\mathbf{j} \times \mathbf{B}$ force can cause an increase in drag. For flow down an inclined plate, where there can be no applied pressure driving the flow, this results in a thickening and slowing down of the flow. More complicated magnetic field and flow geometries are considered in Ref. 40 where the effects of magnetic field gradients are especially emphasized.

Similar to the effect of magnetic fields on turbulence is the stabilizing effect of magnetic fields at the free surface. It has been shown both theoretically and experimentally that a constant strong magnetic field can stabilize an otherwise wavy free surface, resulting in a smooth flow. For the flow described in the preceding paragraph, Hsieh⁴¹ found that for high Ha , the surface is stable to long wavelengths provided that

$$Re < \frac{\exp(2Ha)}{4} \cot \theta \quad (11-88)$$

where Re is the Reynolds number of the flow and θ is the angle of inclination of the plate to gravity. This is a much greater range of Reynolds number than the classical non-MHD result of $Re < 5/4 \cot \theta$.

Applications in Metals Processing. Metals processing requires the handling of large amount of liquified metals in a controlled manner. Certainly the MHD devices discussed above, for example, pumps and flowmeters, will have manifold applications in this industry. But it is also possible to actively control the shape of a free surface by use of high-frequency ac magnetic fields.

A high-frequency magnetic field in the region around an electrical conductor, like a liquid metal, takes a finite time to penetrate into the conductor. It is easily seen from Eq. (11-23) in the limit of slow motion of the liquid $\mathbf{u}$ as compared to the sinusoidal oscillation frequency ω , that:

$$\frac{B}{\tau} \cong \frac{1}{\sigma_f \mu_m} \frac{B}{\delta^2} \quad (11-89)$$

If the characteristic time τ is taken as $2\omega^{-1}$, then the skin depth $\delta \equiv (2/\sigma_f \mu_m \omega)^{1/2}$. This means that if δ is small, the field cannot penetrate far into the conducting medium during the oscillation period of the ac field. In reality, currents induced in the skin region act to nullify the applied field variation. The resulting $\mathbf{j} \times \mathbf{B}$ force can have both a pressure-like component and a tangential stress component. The pressure component can be applied to the free surface in such a way to deflect and shape jets of liquids issuing from a nozzle and even levitate an entire melt. The tangential stress components can be used to induce motion and stir the melt as desired. The induced currents can also provide significant Joule heating in the skin region.

Using a combination of all these effects, it is possible to design various MHD devices like levitating, self-stirred, induction furnaces where the LM never comes in contact with a solid crucible surfaces, and MHD granulators where free LM jets or sheets decay into droplets that then solidify into powders. The interested reader is referred to Davidson,³ Moreau,¹³ and Kolesnichenko² for more detailed mathematical descriptions of these problems with more complete bibliographies.

11.10.4 Gaseous MHD

Introduction. Since 1959, substantial effort has been devoted to exploring the conditions under which a conducting gas moving through a magnetic field might generate useful electrical power. The primary

motivation for the development and use of MHD generators in central-station power plants is the production of power at lower cost through reduced fuel costs per unit of energy produced, traded off against additional capital and operating costs. Operation at high thermal conversion efficiency provides the added benefit of reduced thermal discharge from the plant, thus reducing thermal pollution as compared with conventional steam plants with $\eta \sim 40\%$ or nuclear plants with efficiency as low as 30%.

As originally envisioned, the MHD generator was a "topping" unit on an otherwise conventional steam turbine-generator station. In this case, electric power is generated in the MHD unit, and its exhaust heat, with temperature as high as 2,200 K, is used to generate steam. The limiting Carnot efficiency for such a station might be raised from a maximum of about 65% ($T_1 = 850$ K, $T_2 = 300$ K) upward toward 85% ($T_1 = 2,600$ K, $T_2 = 420$ K). The net efficiency of the combined cycle can be expressed as $\eta_1 + \eta_2(1 - \eta_1)$, where η_1 is the efficiency of the MHD generator and η_2 is the efficiency of the "bottom" steam plant. Typical values are $\eta_1 = 0.25$ and $\eta_2 = 0.4$, for an overall efficiency of 0.55.

Perhaps the greatest importance of the MHD steam plant, as now envisioned, is its potential for very low air pollution while burning high-sulfur coal.⁴² The SO_2 , NO_2 , and particulate emissions are all reduced to very low levels by their interaction with the MHD "seed" material. In pilot plant tests, 2.2 wt.% sulfur coal was burned in a cyclone furnace at 2,200°C with seed concentration of 1 g · mole $\text{K}_2\text{CO}_3/\text{kg}$ coal with 99.8% removal of SO_2 , leaving only 5 ppm SO_2 in the gaseous effluent. This occurs because of an affinity that the potassium seed material has for SO_2 . So seed recovery in the MHD system, which is necessary for economic reasons, also removes the SO_2 . The seed removal costs are calculated as approximately one-fifth of the SO_2 removal costs in a conventional coal-fired plant. In the same tests, through the use of 2-stage combustion, NO_x emissions were reduced below 150 ppm, and complete combustion of CO was achieved.^{42,43}

Table 11-21 summarizes the main features of both open and closed cycle systems which remain the subject of both theoretical and experimental investigation. Generally, practical designs have dc output taken from electrodes at the sides of the MHD channel. Ac power is obtained using electronic inverters.

In the remainder of this section, we first review the main generator configurations used in MHD power generation, together with their governing electrical equations. Flow behavior is described for an example case, using the segmented-electrode Faraday type of generator. Following this, properties of seeded gases are given, and finally the major engineering issues for electrodes and magnets are summarized.

Generator Configurations. Figure 11-81 depicts the basic elements of a generic MHD generator, having quasi-one-dimensional flow of partially ionized gas channeled through a perpendicular, static magnetic field. For this geometry, $\mathbf{u} = \hat{\mathbf{x}} u_x$ and $\mathbf{B} = \hat{\mathbf{z}} B_z$. In the general case, the components of Ohm's Law (Eq. 11-22) are

$$j_x = \sigma \varepsilon_x - \mu_e j_y B_z \quad (11-90)$$

$$j_y = \sigma \varepsilon_y - \sigma u_x B_z + \mu_e j_x B_z \quad (11-91)$$

$$j_z = \varepsilon_z = 0 \quad (11-92)$$

TABLE 11-21 Gaseous MHD Power Generating System Features

	Open cycle	Closed cycle
Heat Source	Coal Manufactured gas Natural gas H_2 Fuel oil	Gas-cooled nuclear reactor Coal Natural gas Fuel oil
Working Fluid	Potassium-seeded combustion products	Cesium-seeded helium
Temperature	$\sim 2500^\circ\text{C}$	$\sim 1400^\circ\text{C}$
Magnetic Field	DC superconducting	DC superconducting
Source	magnets, 4–6 T	magnets, 4–6 T

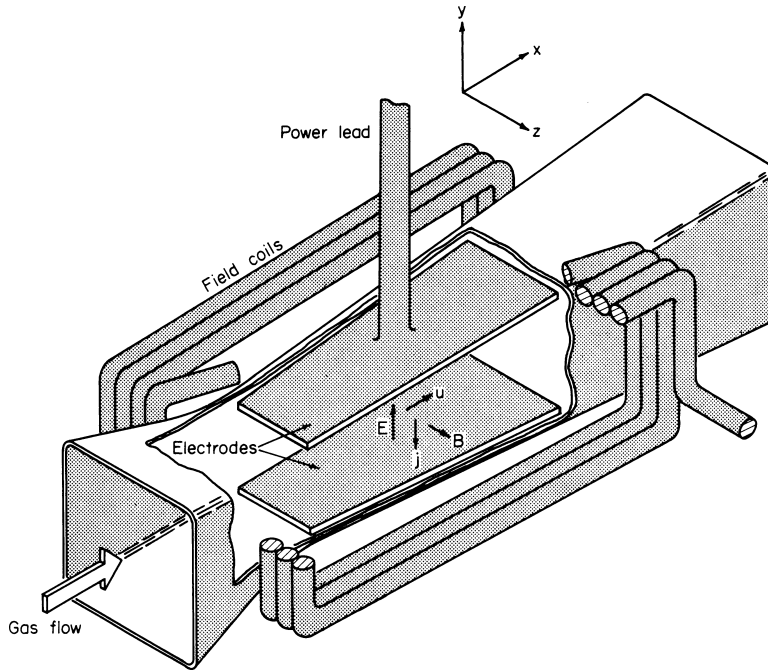


FIGURE 11-81 Basic elements of a magnetohydrodynamic generator.

Four alternative generator configurations are considered here and depicted in Fig. 11-82:

- (a) Segmented-electrode Faraday generator
- (b) Continuous-electrode Faraday generator
- (c) Hall generator
- (d) Diagonally connected generator

(a) *Segmented-electrode Faraday generator.* Configurations in which the circuit for j_y is completed through the external load are called *Faraday generator* configurations. If the electrodes are segmented along the x -direction in order to electrically isolate each pair, then the Hall current is suppressed ($j_x \approx 0$).

Assuming uniform conditions across the channel, the open circuit voltage ($j_y = 0$) is given by Eq. (11-91):

$$V_{oc} = -\int_0^d \varepsilon_y dy = -\int_0^d u_x B_z dy = -u_x B_z d \quad (11-93)$$

and the load power generated is

$$P_L = j_y \varepsilon_y = -\sigma(u_x B_z - \varepsilon_y) \varepsilon_y = -\sigma u_x^2 B_z^2 (1 - K) K \quad (11-94)$$

where the dimensionless loading parameter K is defined by $K = \varepsilon_y / u_x B_z$. Using Eq. 11-56, we find that the conversion efficiency is

$$\eta_e = \frac{j_y \varepsilon_y}{u_x j_y B_z} = \frac{\varepsilon_y}{u_x B_z} = K \quad (11-95)$$

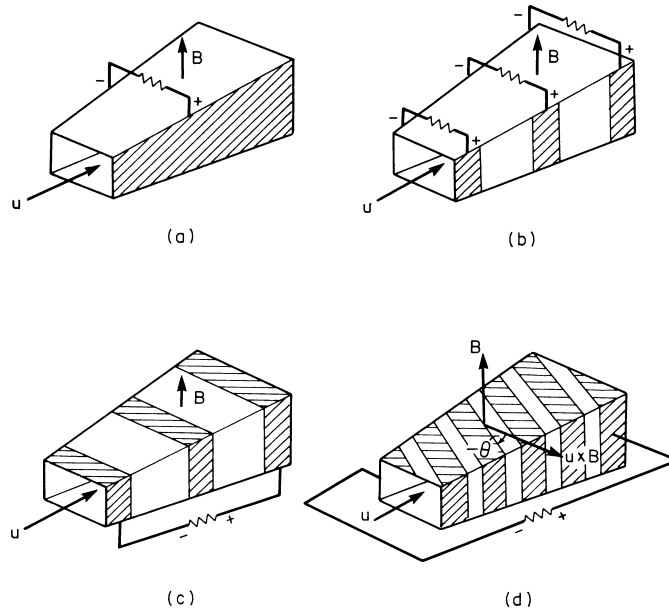


FIGURE 11-82 Generator configurations: (a) segmented-electrode Faraday generator; (b) continuous-electrode Faraday generator; (c) Hall generator; and (d) diagonally-connected generator.

(b) *Continuous-electrode Faraday generator.* In a continuous-electrode generator, $\varepsilon_x = 0$ and the Hall current is finite, $j_x \neq 0$. The x -component of current (in the direction of the fluid flow) has its circuit completed through the electrode walls. The j_y component is reduced due to this effect:

$$j_x = -\mu_e j_y B_z$$

$$j_y = \frac{\sigma}{1 + \omega^2 \tau^2} (\varepsilon_y - u_x B_z) = \frac{\sigma u_x B_z}{1 + \omega^2 \tau^2} (1 - K) \quad (11-96)$$

The load power is:

$$P_L = j_y \varepsilon_y = \frac{\sigma}{1 + \omega^2 \tau^2} (\varepsilon_y - u_x B_z) \varepsilon_y = -\frac{\sigma u_x^2 B_z^2}{1 + \omega^2 \tau^2} (1 - K) K \quad (11-97)$$

The open-circuit terminal voltage is the same for both types of Faraday generator, as is the local electrical efficiency, $\eta_e = K$. However, the power density is reduced by $1 + \omega^2 \tau^2$ when the electrodes are continuous.

(c) *Hall generator.* In the Hall generator configuration, opposing electrode pairs are short circuited ($\varepsilon_y = 0$), and the circuit for j_x is completed through the external load. In this case, the current components derived from Eqs. (11-90) to (11-92) are

$$j_x = \frac{\sigma}{1 + \omega^2 \tau^2} (\varepsilon_x + \omega \tau u_x B_z) \quad (11-98)$$

$$j_y = \frac{\sigma}{1 + \omega^2 \tau^2} (\omega \tau \varepsilon_x - u_x B_z) \quad (11-99)$$

The open circuit voltage ($j_x = 0$) across the full channel length is given by

$$V_{oc} = - \int_0^L \varepsilon_x dy = \int_0^L \omega \tau u_x B_z dx = \omega \tau u_x B_z L \quad (11-100)$$

In this case, the Hall loading parameter is written $K_H = -\varepsilon_x / \omega \tau u_x B_z$, so that the load power generated is

$$P_L = j_x \varepsilon_x = \frac{\sigma}{1 + \omega^2 \tau^2} (\varepsilon_x + \omega \tau u_x B_z) \varepsilon_x = \frac{\sigma \omega^2 \tau^2 u_x^2 B_z^2}{1 + \omega^2 \tau^2} (1 - K_H) K_H \quad (11-101)$$

The conversion efficiency is

$$\eta_e = \frac{j_x \varepsilon_x}{u_x j_y B_z} = \frac{(1 - K_H) K_H}{K_H + 1/\omega^2 \tau^2} \quad (11-102)$$

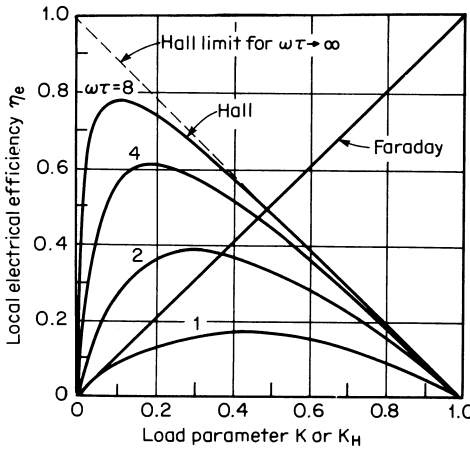


FIGURE 11-83 Comparison of local electrical efficiencies of Faraday and Hall generators.

A comparison between Faraday and Hall generator efficiencies is given in Fig. 11-83. Good efficiency in a Hall generator requires high $\omega \tau$ and a small loading parameter, whereas the Faraday generator efficiency is independent of $\omega \tau$ and improves with higher values of the loading parameter.

(d) *Diagonally-connected generator.* A configuration that has been favored recently is diagonal connection of electrodes along equipotential surfaces at the angle $\theta = \tan^{-1} \varepsilon_y / \varepsilon_x$ with respect to the vector $\mathbf{u} \times \mathbf{B}$. Ideally, with this configuration, the Hall current is zero, and the electrode voltage between opposite pairs is the same as for the Faraday generator. With the diagonal connections, the overall circuit is a series connection of multiple Faraday-generator electrodes. The output, at comparatively high voltage, is taken between the first and last electrodes in the series.

The characteristics of the diagonally connected generator are intermediate between those

of the Hall and Faraday generators. Allowing for a finite Hall current, the current components in their most general form are

$$j_x = \frac{\sigma}{1 + \omega^2 \tau^2} [\varepsilon_x - \omega \tau (\varepsilon_y - u_x B_z)] = \frac{\sigma u_x B_z}{1 + \omega^2 \tau^2} \omega \tau (1 - K) - \frac{K}{\tan \theta} \quad (11-103)$$

$$j_y = \frac{\sigma}{1 + \omega^2 \tau^2} (\omega \tau \varepsilon_x + \varepsilon_y - u_x B_z) = - \frac{\sigma u_x B_z}{1 + \omega^2 \tau^2} \left(1 - K + \frac{\omega \tau K}{\tan \theta} \right) \quad (11-104)$$

The condition $j_x = 0$ is satisfied if

$$K = \frac{\omega \tau \tan \theta}{1 + \omega \tau \tan \theta} \quad (11-105)$$

In this case, the local electrical efficiency is $\eta = K$.

Energy Extraction and Flow Relations. In general, numerical solutions are needed to solve the complete set of equations governing power generation and flow. The simple case of a quasi-one-dimensional

constant-velocity ideal gas flow is examined here in closed form in order to provide insight into the flow behavior. The velocity is maintained constant as the gas expands by adjusting the flow area A_c such that mass conservation leads to

$$\frac{d}{dx}(\rho A_c) = 0 \quad (11-106)$$

A Faraday generator configuration with segmented electrodes is assumed. In this case, the Hall current vanishes and Ohm's Law can be written as

$$j = \sigma(\varepsilon - uB) = -\sigma uB(1 - K) \quad (11-107)$$

The pressure variation is linear for a constant field:

$$\frac{dp}{dx} = jB = -\sigma uB^2(1 - K) \quad (11-108)$$

The solution can be written in terms of the pressure at the inlet ($x = 0$):

$$\frac{p}{p_o} = 1 - \frac{x}{L_i} \quad (11-109)$$

$$L_i = \frac{1}{1 - K} \frac{p_o}{\sigma uB^2} \quad (11-110)$$

where L_i is the "interaction length,"⁴⁴ which is an approximate measure of the channel length required to extract an appreciable amount of the gas energy.

The energy equation can be used to determine the temperature variation along the duct. The total fluid enthalpy (per unit mass) is the sum of the kinetic energy, internal energy, and static pressure:

$$H = u^2/2 + e + p/\rho \quad (11-111)$$

Conservation of energy equates the rate of change of fluid energy with the electric power dissipated:

$$\rho \frac{dH}{dt} = \mathbf{j} \cdot \varepsilon \quad (11-112)$$

With constant velocity, we can replace H by the static enthalpy h :

$$h = H - u^2/2 \quad (11-113)$$

For an ideal gas, $h = C_p T$, so that the energy equation becomes:

$$\rho C_p u \frac{dT}{dx} = j\varepsilon \quad (11-114)$$

We can replace the current density and electric field in Eq. (11-114) using Eq. (11-31) and the definition of the loading parameter, $K = \varepsilon/uB$:

$$\rho C_p u \frac{dT}{dx} = \frac{1}{B} \frac{dp}{dx} \cdot uBK \quad (11-115)$$

Solving for K ,

$$K = \rho C_p \frac{dT}{dp} \quad (11-116)$$

For an ideal gas, the temperature and pressure are related by

$$C_p T = \frac{\gamma}{\gamma - 1} \frac{p}{\rho} \quad (11-117)$$

If we use Eq. (11-116) to replace p in Eq. (11-117), we find

$$\frac{dT}{T} = K \left(\frac{\gamma - 1}{\gamma} \right) \frac{dp}{p} \quad (11-118)$$

This can be integrated to give the relation between p and T :

$$\frac{T}{T_o} = \left(\frac{p}{p_o} \right)^{K(\gamma-1)/\gamma} \quad (11-119)$$

The pressure, temperature, flow area, and Mach number are plotted in Fig. 11-84. The Mach number is (11-120)

$$M = \frac{u}{c_s} = \frac{u}{\sqrt{\gamma P/\rho}} = \frac{u}{\sqrt{\gamma R T / W_m}}$$

where c_s is the local speed of sound, R is the universal gas constant, and W_m is the molecular weight of the gas. For constant velocity:

$$\frac{M}{M_o} = \left(\frac{T}{T_o} \right)^{1/2} = \left(\frac{p}{p_o} \right)^{K(\sigma-1)/2\sigma} \quad (11-121)$$

Working Fluid Conductivity. Conductivity of the working fluid is a critical parameter in a gaseous MHD topping unit. The conductivity is obtained by summing the contributions from each species. However, electrons contribute most of the conductivity due to their higher mobility.

$$\sigma = n_e e \mu_e = \frac{n_e e}{m_e \nu} \quad (11-122)$$

At low ionization states, the electron mobility is inversely related to the collision frequency with neutral particles. As the degree of ionization increases, the mobility is reduced by electron-ion and

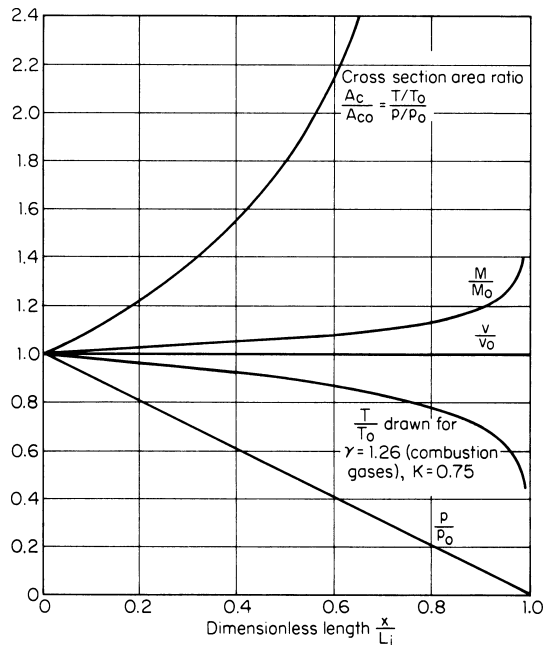


FIGURE 11-84 Dimensionless ratios vs. normalized length (x/L_i) in an ideal, constant-velocity channel.

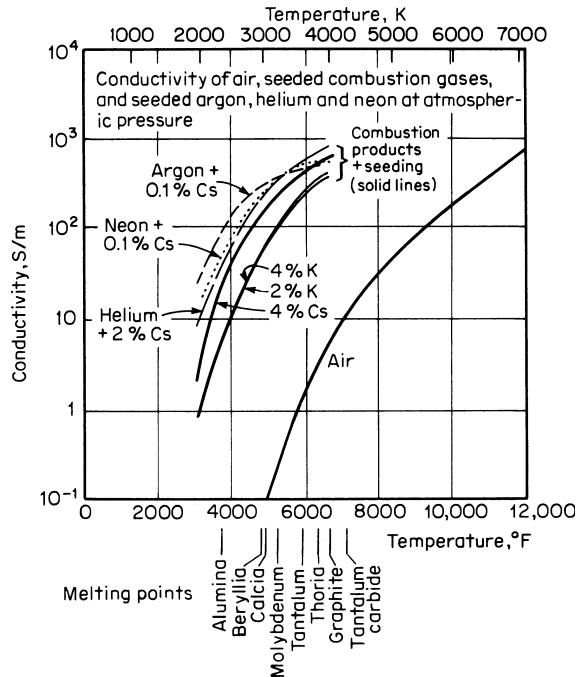


FIGURE 11-85 Conductivity of air, seeded combustion gases and seeded argon, helium, and neon at atmospheric pressure. (All curves, except for air, are from Ref. 46.)

electron-electron collisions, which have higher cross sections. At only 1% ionization, already this effect becomes significant. Therefore, a high degree of ionization is not necessary to achieve an appreciable fraction of the fully ionized conductivity.

Temperatures for fossil-fuel combustion are in the range of 2,500 to 3,000 K. At these temperatures, thermal ionization of air, combustion product gases, or inert gases is so low that the electron density is orders of magnitude below that is necessary to obtain suitable conductivity (see Fig. 11-85). One might obtain marginally acceptable conductivity by reducing the gas pressure, however, this also would result in larger duct and heat-exchanger sizes.

Fortunately, a large increase in conductivity can be obtained by seeding the gas with a small percentage of materials with much lower ionization potential. The ionization potential of the outermost electron in air is ~ 14 V, and that of inert gases is even higher. Alkali metals make exceptional seed materials, with ionization potential of 3.89 V for cesium, 4.34 V for potassium, and 5.4 V for lithium. Some calculated conductivities of seeded gases are shown in Fig. 11-86 as a function of temperature and pressure. In general, these curves are in close agreement with measured values (e.g. Ref. 45)

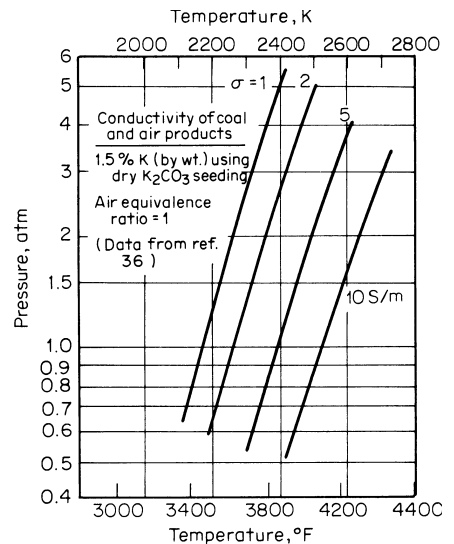


FIGURE 11-86 Conductivity vs. temperature and pressure for seeded coal products and air using 1.5 wt.% K, obtained using dry K_2CO_3 . (Adapted from Ref. 46.)

Unfortunately, alkali metals also carry a relatively high collision cross section, such that an increasing percentage of seed atoms not only increases the electron density but also decreases the mobility. An optimal seeding percentage is reached at about 0.1% for cesium and potassium in argon and about 0.3% in neon.⁴⁶

11.10.5 2-Phase MHD

Flow Characteristics. MHD of conducting 2-phase mixtures, consisting of liquid and gas phases, raises new phenomena providing the potential for unique applications. 2-Phase mixtures may arise from boiling or from mixing of distinct gas and liquid phases—for example, helium mixed with a liquid metal. Here we summarize the basic flow characteristics of 2-phase mixtures and the application to liquid metal MHD (LMMHD) for power conversion.

Much of the early progress studying 2-phase flows was based on empirical results,^{47–50} since the underlying flow structures can be very complex. Similar to single-phase flows, the effect of the magnetic field is to suppress turbulence and to alter the velocity profiles. In addition, modifications in the interface configuration and slip between phases occur, and the transition between flow regimes can be shifted.

Typical 2-phase flow patterns are depicted in Fig. 11-87. As in ordinary 2-phase flow, increasing superficial gas velocity causes the flow to transition from bubbly, to churn, to slug, and finally to annular mist flow regimes.⁵¹ However, observable differences between MHD and non-MHD behavior occur, as summarized in Fig. 11-87.

MHD Generators and Power Conversion. Liquid metal MHD power conversion using 2-phase mixtures was contemplated as early as the 1960s.⁵² In the 1970s, an extensive program was conducted at Argonne National Laboratory (ANL),^{50,53–56} culminating in the development of a constant-velocity dc Faraday generator using N_2 with Na or NaK. Following this early work, a rather extensive program was initiated at Ben-Gurion University, where a variety of power conversion systems have been analyzed and/or tested.⁵⁵

The use of liquid metals for power conversion avoids the very high temperatures required to maintain an ionized gas in the conducting state. In that case, practically any heat source can be used, including solar, geothermal, nuclear, or even coal combustors. In addition, the higher conductivity of liquid metals makes possible higher power density with moderate magnetic fields, so that relatively small sized generators are possible. For example, liquid metals offer conductivities of the order of 10^6 to 10^7 ($\Omega \cdot m$)⁻¹ at low temperature, as compared with 10 ($\Omega \cdot m$)⁻¹ for the case of He seeded with 0.45% Cs at 2,000 K. Considerable support has been obtained for research on space-based power supplies, due in part to these advantages.⁵⁶

In general, a thermodynamic cycle requires a working medium (or “thermodynamic medium”) that can expand and contract with temperature, for example, gas or steam. For MHD power conversion, the thermodynamic fluid is mixed with an electrodynamic fluid (the liquid metal) to allow MHD generation.

Because the heat capacity of the liquid phase significantly exceeds the gas phase, 2-phase flow expansion (and compression) occurs nearly isothermally. This results in potentially higher thermal conversion efficiency, approaching that of the ideal Carnot cycle. For example, Fig. 11-88 compares a standard gas Brayton cycle T - s diagram with a modified cycle using a LMMHD generator.

Several classes of thermodynamic cycles are possible, depending on the types of coolant (e.g., gas, liquid, and/or 2-phase fluid), the use of evaporation or gas mixing, and the use of bottom cycles. These are summarized in Table 11-22.

In the “homogeneous cycle,” the thermodynamic and electrodynamic fluids remain mixed throughout the cycle (Fig. 11-89). The heat source causes the working fluid to evaporate, which drives expansion through the 2-phase generator.

In an Ericsson cycle, a mixer/separator combination provides the ability to operate over wider temperature ranges. The main steps are depicted in Fig. 11-90. In this example, the top cycle has four main steps: (1) the liquid metal is heated by a heat source; (2) a mixer combines the thermodynamic fluid with the liquid metal; (3) the mixture is expanded through a generator; and (4) the two phases

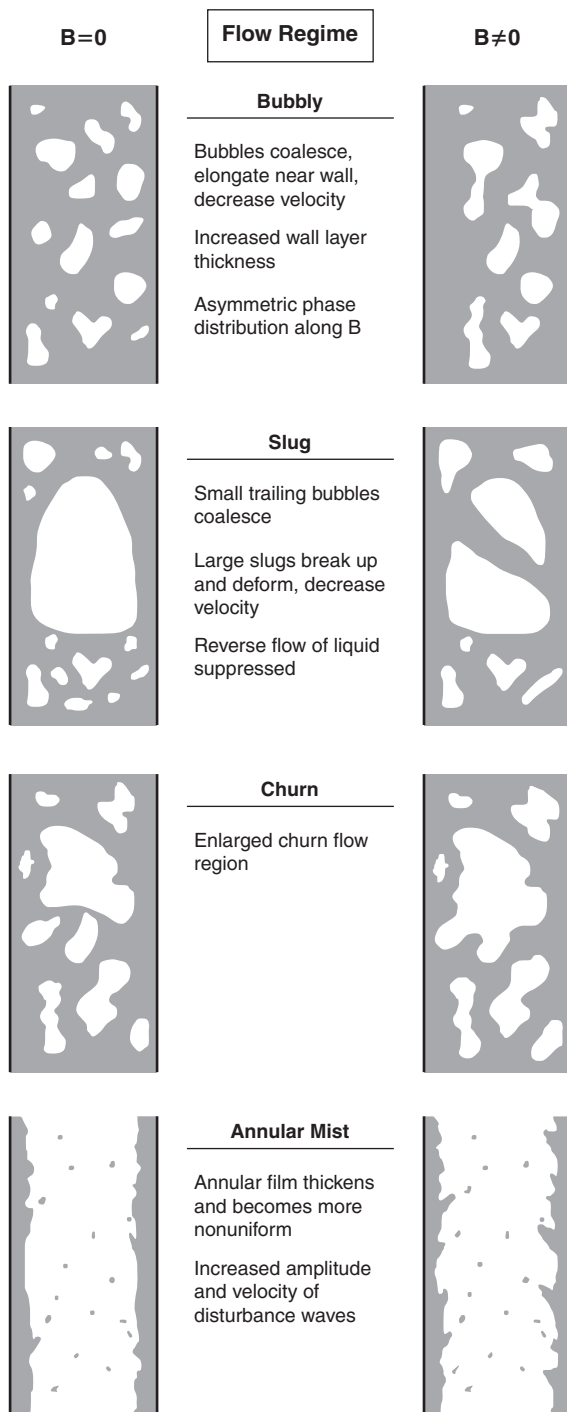


FIGURE 11-87 Effect of magnetic field on 2-phase flow regimes.

1. recuperator (heated side)
2. heat source
3. turbine or LMMHD generator
4. recuperator (cooled side)
5. heat rejection
6. compressors and intercoolers

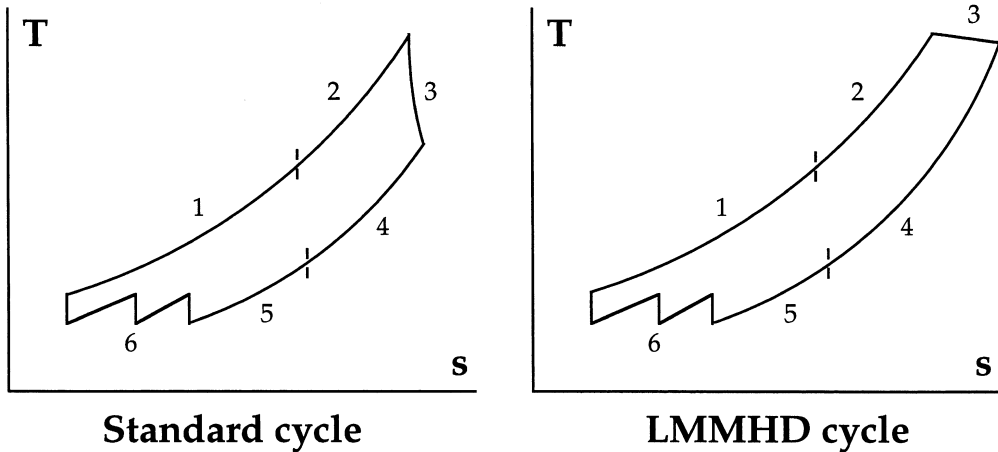


FIGURE 11-88 Standard Brayton cycle compared with MHD Brayton cycle.

are separated. The gas side of the cycle may itself take advantage of the useful heat by expansion through a Brayton cycle turbine, or it could utilize a 2-phase MHD compressor.

In the Rankine cycle, typically water is injected into a chemically compatible liquid metal (such as a lead-alloy). A steam turbine and/or 2-phase generator is used for electric generation.

11.10.6 Nomenclature

a	channel half-width parallel to B
b	channel half-width perpendicular to B
B	magnetic field intensity
B_o	characteristic field strength, used to nondimensionalize equations
c_e	RMS electron thermal velocity in a Maxwellian distribution, $(3kT/m_e)^{1/2}$
c_s	speed of sound
e	charge on an electron

TABLE 11-22 LMMHD Cycles and Possible Working Fluids⁵⁵

Cycle type	Working fluids
Homogeneous cycles	Na, K, Cs, etc.
Ericsson cycle with LMMHD compressor or Brayton gas turbine/compressor	Na/He, Li/He
Rankine cycles with or without steam turbine	Pb-alloy/steam
Binary cycles (e.g., homogeneous top plus Rankine bottom)	

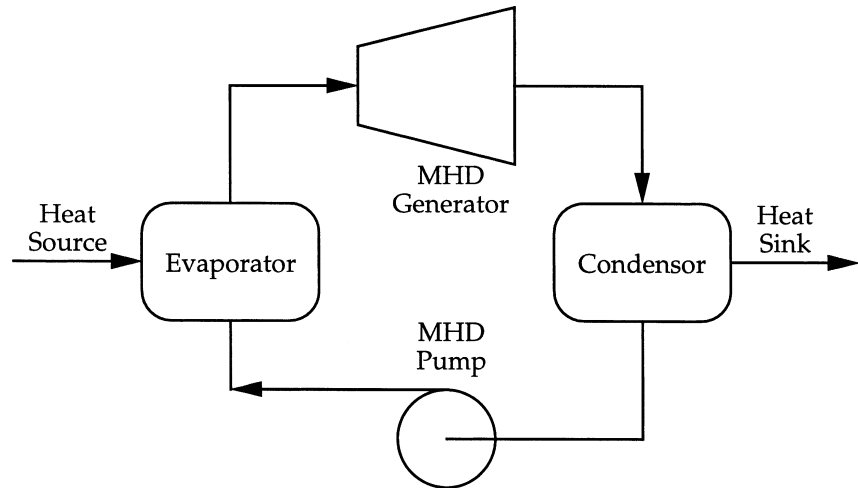


FIGURE 11-89 Homogeneous LMMHD cycle.

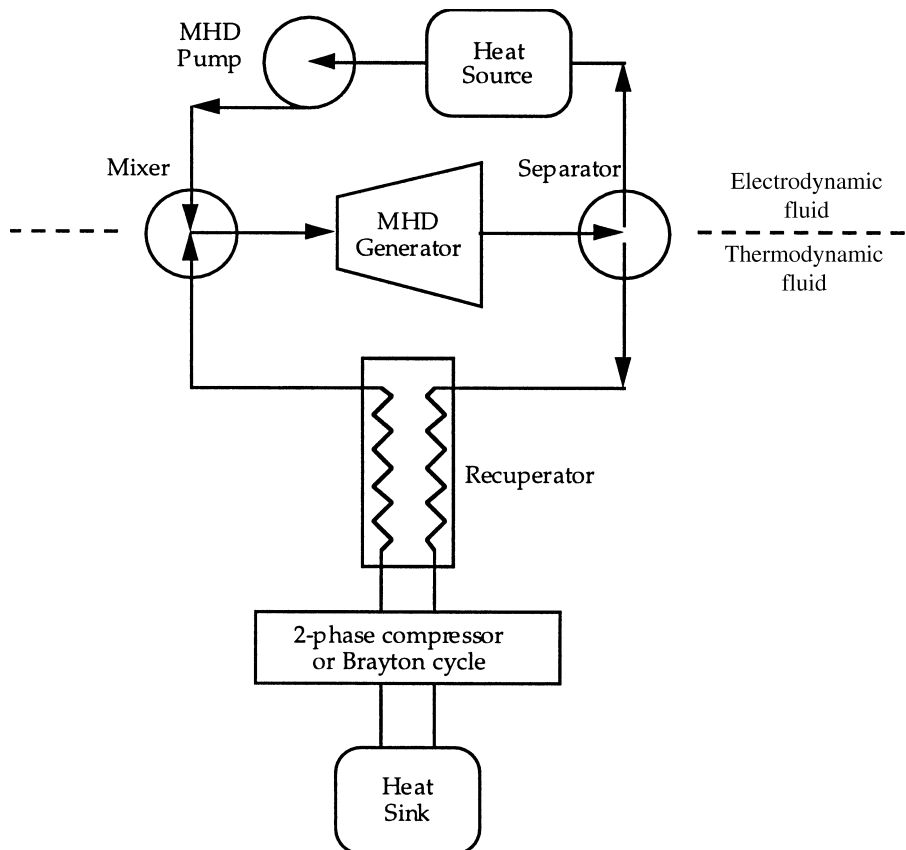


FIGURE 11-90 Modified Ericsson cycle with LM heating.

Ha	Hartmann number, $aB\sqrt{\sigma/\mu_f}$
j	current density
j_f	current density in fluid
J_w	current density in wall
k	Boltzmann constant
K	loading parameter
K_H	Hall loading parameter
l	length
m	mass
m_e	electron mass
n_e	number density of free electrons
p	fluid pressure
P	pressure gradient
q	electric charge
Re_m	magnetic Reynolds number, $\sigma\mu vl$
R_L	load resistance
T_e	electron temperature
u	fluid velocity
u_e	drift velocity of electrons
v	particle velocity
v_b	bulk average velocity
v_o	characteristic velocity, used to non-dimensionalize equations
V	nondimensional velocity
V_{oc}	open circuit voltage
W_m	molecular weight
X	non-dimensional x coordinate
Y	non-dimensional y coordinate
β	rectangular channel aspect ratio
δ	wall thickness or skin depth
ε	electric field
λ	electron mean free path
μ_e	electron mobility, $\omega\tau/B$
μ_f	fluid dynamic viscosity
μ_m	magnetic permeability
ν	electron-atom collision frequency
ν_f	kinematic viscosity, μ_f/ρ
ρ	fluid density
σ	electrical conductivity
σ_f	electrical conductivity of fluid
σ_w	electrical conductivity of wall
τ	electron mean collision time, λ/C
φ	electric scalar potential
Φ	wall conductance ratio
ω_e	electron cyclotron frequency, $eB/m_e = \mu_e B/\tau$
ω_c	cyclotron frequency

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